Monitoring CO_2 Emissions from HDV in Europe – An Experimental Proof of Concept of the Proposed Methodological Approach

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Abstract

The European Commission in joint collaboration with Heavy Duty Vehicle manufactures, the Graz University of Technology and other consulting and research bodies has been preparing a new legislative framework for monitoring and reporting CO_2 emissions from Heavy Duty Vehicles (HDVs) in Europe. In contrast to passenger cars and light commercial vehicles, for which monitoring is performed through chassis dyno measurements, and considering the diversity and particular characteristics of the HDV market, it was decided that the core of the proposed methodology should be based on a combination of component testing and vehicle simulation. Emphasis is put on accurately simulating the performance of different vehicle components and achieving realistic fuel consumption results. A proof of concept was launched aiming to test and prove that these targets are achievable.

A series of experiments were conducted on 2 different trucks, a Daimler 40ton Euro VI, long haul delivery truck with semi-trailer and a DAF 18 ton Euro V rigid truck. Measurements were performed at the Joint Research Centre's HDV chassis dyno labs and on the road. A vehicle simulator (Vehicle Energy Consumption Calculation Tool - VECTO) has been developed to be used for official monitoring purposes and the results of the measurements were used for its validation. As inputs the simulation based methodology considers test track measurement of driving resistances (eg air drag), determination of drivetrain losses (e.g. gearbox), determination of power demand of engine auxiliaries (eg. cooling fan) and other consumers (e.g. steering pump), measurement of the engine fuel consumption map as extension to the engine's type approval tests (as described in EURO VI legislation). CO_2 emissions of the vehicle are then calculated using the aforementioned input data for predefined representative driving cycles and mission profiles.

For the two Heavy Duty vehicles tested and simulated on the same test route, fuel consumption 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%), it is concluded that a future certification scheme can be based on vehicle simulation tools.

Introduction

Heavy-Duty Vehicles (HDV) represent about a quarter of the European Union's (EU) road transport CO_2 emissions and some 6% of the total CO_2 emissions. In spite of some improvements in fuel efficiency in recent years, overall HDV CO_2 emissions are still rising, mainly due to increasing road freight traffic. The need for a strategy addressing CO_2 emissions from the transport sector has been recognized by the European Commission (EC) in its 2010 Strategy on Clean and Energy Efficient Vehicles. Moreover, the EC's 2011 White Paper on transport (EC 2011) describes a pathway to increase the sustainability of the transport system with technological innovation, enabling the transition to a more efficient and sustainable European transport system.

One key factor for achieving such targets is a robust CO_2 and fuel consumption monitoring method that reflects to the best possible extent the actual performance of the vehicles over real operating conditions and the comparative advantages of different vehicle models and technology packages available in the market. This in turn provides appropriate information to the end user and better supports the introduction into the market of vehicles with lower fuel consumption(AEA-Ricardo 2011). It also allows the collection of valuable information needed for implementing necessary policy measures to facilitate the achievement of the targets set.

While car and van CO_2 emissions (M1-N1 vehicles) are being measured according to an agreed method, HDV emissions so far are not measured in a standardized and consistent way. Consequently no reliable baseline as to the actual amount of these emissions exists. To fill this gap, a series of still on-going projects was initiated by EC. Aim of the research performed was the creation of standardized method to quantify and report CO_2 emissions from HDVs. Initial studies and feedback received from OEMs suggested that the approach that best fits the characteristics and particularities of the HDV sector is through computer simulation. Important steps have been done in the past three years in this direction with the development of a beta version of an appropriate vehicle simulator (Fontaras et al. 2013) and also the necessary test protocols for measuring individual vehicle components and producing the input data needed for running the simulations(TU Graz 2012, Kousoulidou et al. 2013). Similar approaches have already been adopted by other major markets such as US and Japan(Sharpe and Lowell 2012).

In order to investigate the plausibility of such a simulation-based approach an extensive experimental study was launched, also referred to as Proof of Concept study. This paper summarizes the findings of the study and attempts mainly to investigate the effectiveness of the monitoring methodology regarding issues related to accuracy, repeatability and reproducibility for the quantification of fuel consumption from complete HDV but also investigate whether a simulation based methodology can serve the needs of CO_2 monitoring, certification, labelling and standards for complete HDVs.

Methodology

Two series of tests were performed in order to assess the quality of the proposed CO_2 (Clima 2014, Luz et al. 2014) monitoring approach, measurements under highly controlled conditions on the JRC heavy duty vehicle chassis dyno and measurements under realistic conditions on the road.

Test Vehicles

Two vehicles were used in this study, a 40 t Euro VI tractor-trailer Daimler Actros and a 18 t DAF CF75 Euro V (see Table 1). Both vehicles were provided by the OEMs in standard operating configuration.

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
Engine displacement [l]	12.8	9.2

a b

Figure 1: Vehicles used in the study a: Actros tractor-trailer, b: CF75 rigid truck

Chassis dyno tests

All chassis dyno measurements were performed at the Vehicle Emissions Laboratory (VELA7) of the European Commission's Joint Research Centre. VELA 7 is equipped with a chassis dynamometer (Zoellner GmbH, Germany) that can host trucks and buses of up to 40t in gross vehicle 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 m^3/min in order to achieve a maximum air flow of 150 m^3/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, CH2, LH_2, LPG, LNG and CNG. For the analysis of pollutant emissions an AVL i60 AMA 4000 system is used. In addition to the standard instantaneous CO_2, instantaneous fuel consumption was measured also with an AVL KMA Mobile fuel flow meter (AVL 2014).

The 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 regional delivery cycle (RDC) proposed to be included in the forthcoming CO_2 monitoring and reporting legislation as a representative cycle for rural delivery conditions in Europe, and the FIGE driving cycle. The cycle profiles are demonstrated in Figure 2.

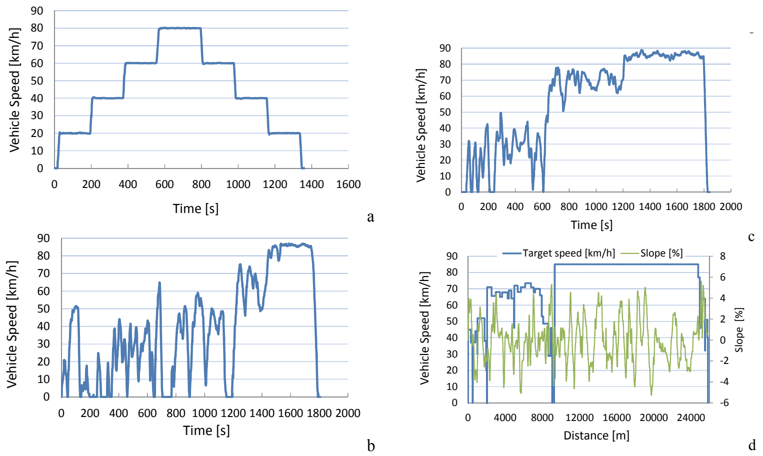

Figure 2: Steady state modes (a), WHVC (b), FIGE (c) and proposed RDC (d)

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.

On-road tests

Route characteristics

The route used for the on road tests on both vehicles is presented in Figure 3.

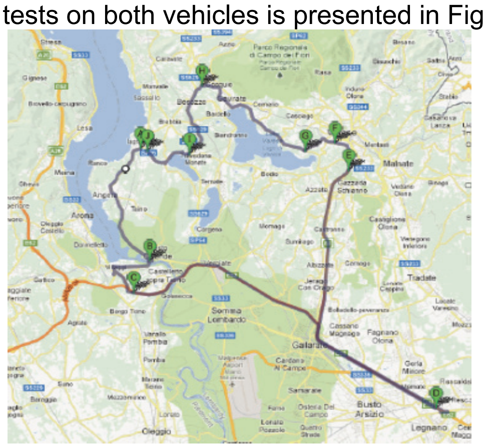

Figure 3: Drive path of the on-road tests performed (A→C: warm up section, C→D→E: highway conditions, E→G: urban conditions, G→J: rural driving)

The 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 2.

Table 2: 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%**

Test instruments

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. The PEMS consisted of a set of analysers and an exhaust flow meter used to measure the exhaust mass flow. In respect to this, the system used in this project employs a mass flow meter (EFMs) equipped with differential pressure devices and thermocouples which measure the exhaust temperature. The relationship between the differential pressure, the temperature and the exhaust mass flow is based on the Bernoulli principle. The EFM accuracy over a typical test cycle is better than ±3.0%, with a resolution of 0.003 m^3/min and an exhaust temperature range that goes from ambient to 550 °C. The flow meter was installed at the outlet of the tailpipe using modified cycle racks to secure the device to the vehicle body. The measurement of instantaneous CO_2 was performed with a NDIR analyser which operated on a 0–20% range exhibiting an accuracy of ±3% of reading.

Due to technical 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.

In order to obtain an accurate picture of the conditions and the vehicle's operation during the on-road tests, specific equipment was used in addition to the standard PEMS or on road instrumentation. A mobile anemometer (Table 3) was used for measuring the air flow velocity and angle

Table 3: Anemometer characteristic

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

For a more accurate measurement of the road loads imposed on the vehicle during the on-road and chassis dyno testing, both vehicles were instrumented during all measurements with torque measurement devices. This allowed on a second step a better validation of the forces simulated by VECTO and an assessment of the origin of the inaccuracies in the calculations.

Table 4: 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

Vehicle simulation

VECTO was used as the vehicle simulation application (version 1.1 beta 3). VECTO was developed in order to lay the foundations for the future HDV CO_2 monitoring and certification software application.

The main features of VECTO can be found in (Fontaras et al. 2013, Luz et al. 2014). By the time this paper 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 or regulation oriented simulators (ACEA 2013, Franco 2013, Kousoulidou et al. 2013, Lee and Anderson 2013, Fontaras et al. 2014). Hence the programming and architecture of VECTO, at least in terms of software, should not affect the findings and key conclusions of this analysis.

Results

Chassis Dyno measurements

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 4 summarizes the fuel consumption results measured and simulated over the 3 driving cycles (WHTC, FIGE and RDC). Results are presented normalized against the average values measured with the reference fuel flowmeter (AVL KMA). In the first column (sub figs *a,c,e*), error bars correspond to the standard deviation of the measurement. In addition to the fuel consumption result obtained via the fuel flowmeter in subfigures *c* and *e* the result of 2 other fuel consumption measurement systems are presented (fuel flowmeter installed by the OEM and fuel consumption derived from recorded raw CO_2 emissions.

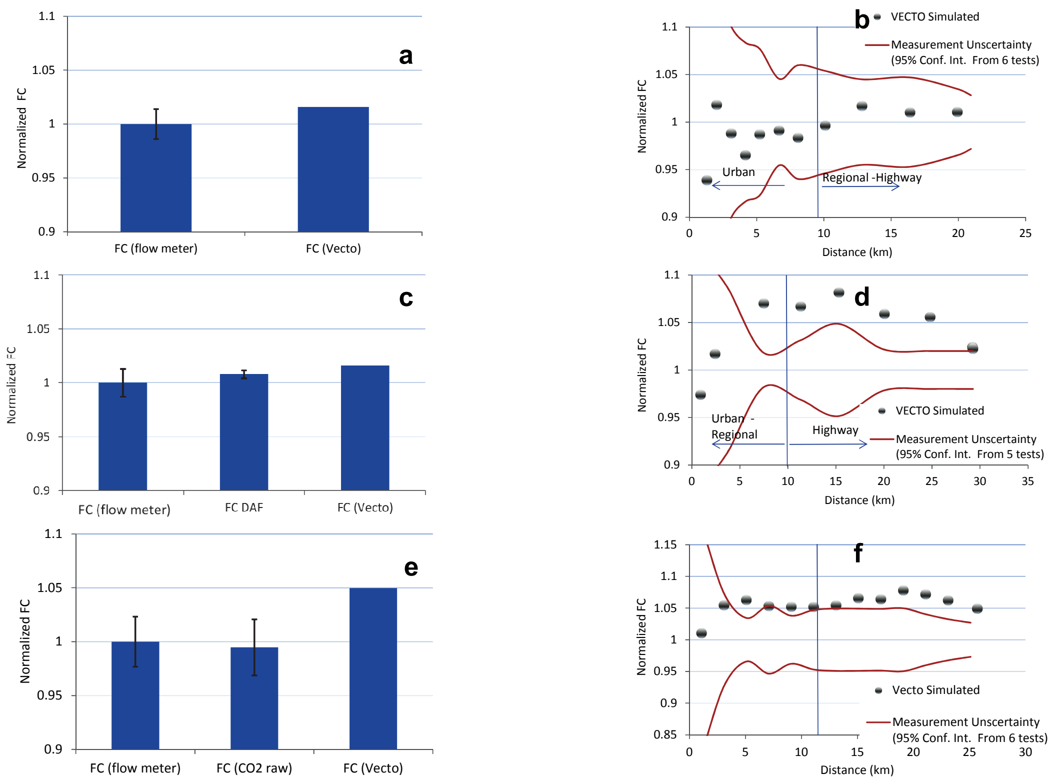

Figure 4: Measured vs simulated results (normalized to the average fuel consumption measured) for WHVC (a-b), FIGE (c-d) regional delivery (e-f). Error bars correspond to ±standard deviation of the measurements (sub figs a,c,e), red lines to the 95% confidence interval of the tests

In subfigures *b,d,f* (second column) the average recorded fuel consumption throughout the cycle is equal to one and red lines correspond to the calculated uncertainty of the measurement on a 95% confidence interval. Green dots represent the simulated fuel consumption at selected points in time during the test.

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 RDC the difference between measured and simulated 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 quite accurately not only over the complete cycles but also for their duration. 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 RDC 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.

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 *5* 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.

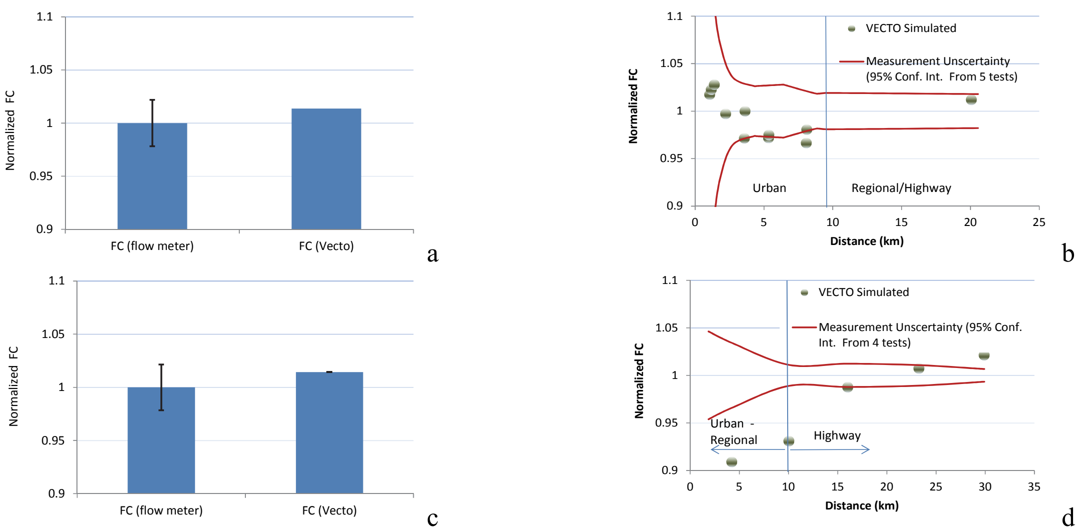

Figure 5: Measured vs simulated results for the driving cycles tested, WHVC (a-b), FIGE (c-d). Error bars correspond to ±standard deviation of the measurements (sub figs a,c,e) whereas red lines to the 95% confidence interval of the tests

For both WHTC and FIGE the overall results were very good, with the measurement-simulation difference remaining at low levels (~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

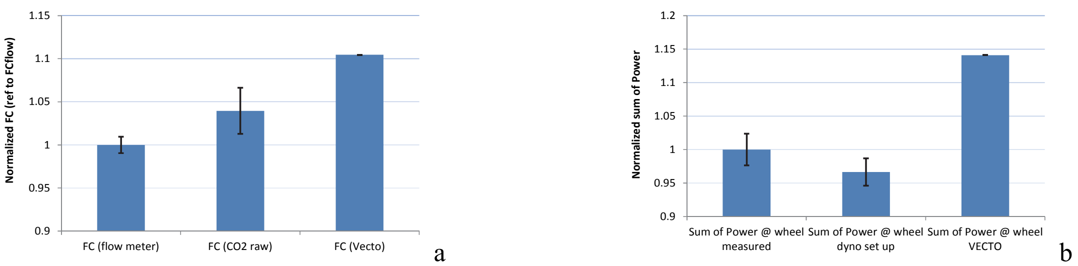

Figure 6: Measured vs simulated results for the RDC (a) and the corresponding measured vs simulated power at wheel (b). Error bars correspond to ±standard deviation of the measurements.

A notable difference between measured and simulated fuel consumption was observed for the RDC, which was in the order of 10% (***Figure 6***a). An analysis of the simulated power at vehicle wheel (***Figure 6***b) 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 (e.g. auxiliaries, gearboxes, drivelines, gear shifting 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.

On Road tests vs VECTO simulations

CF75[1]

Figure 8 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 variability, fact which in combination with the observations from Figure 7 point to good repeatability of the test conditions and the vehicle operation. Finally, the difference between the measurement and VECTO simulation (case 4[2]) was in the order of -1.8%, a very satisfactory figure.

1 All simulations were performed by DAF based on input data provided by the JRC

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

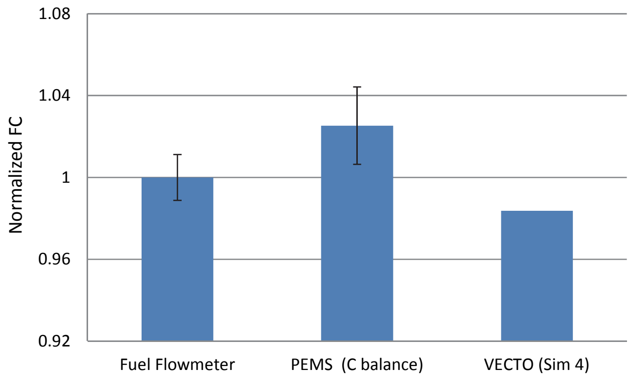

Figure 7: Average fuel consumption as measured over the 4 tests with the KMA fuel flow meter, calculated via C-balance of the exhaust gas measured with PEMS and simulated with Vecto (case 4). All values are normalized against the KMA measured consumption. Error bars show the standard deviation of the 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 CO_2 monitoring methodology. In simulation 2 input parameters were selected to match as closely as possible individual components of the particular vehicle ("best actual parameters" [3]).
- 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 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 9 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).

3 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.

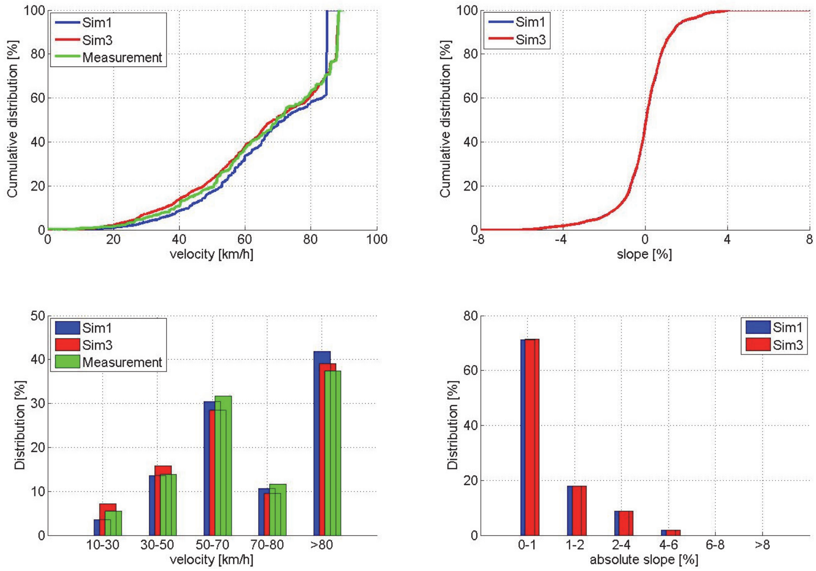

Figure 8: Drive cycle characteristics and speed distributions of Test1 used for simulations and simulation runs 1 and 3

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 10. The abovementioned results are fully in line with those of a similar analysis performed by internally by the OEM.

Table 5: 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%

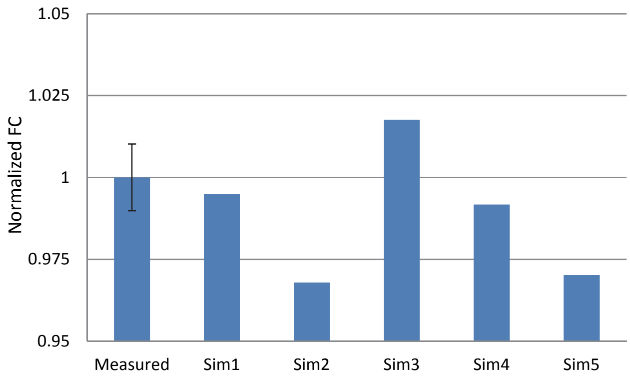

Figure 9: Measured vs simulated fuel consumption for CF75. Error bars correspond to ±σ

A more in depth investigation of the ability of VECTO to reproduce the on road tests is presented in Figure 11. 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).

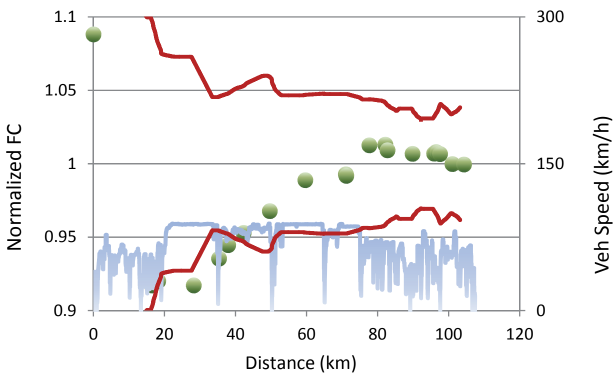

Figure 10: Normalized simulated fuel consumption over trip distance (1=fuel consumption measured during test 1). Green dots correspond to simulation results, while red lines indicate the measurement uncertainty on a 95% confidence interval. The blue trace indicates the speed over distance trace of the 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

From the 3 measurement runs performed on road with this vehicle, 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[4] 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 data series recorded during the reference test were used.

[4] As measured with the on board AIC system

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 12. 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 6.
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.

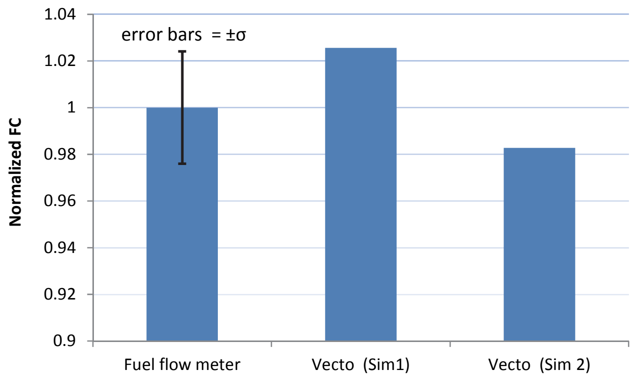

Figure 11: Normalized fuel consumption results for Actros measured vs simulated

Table 6: Summary of simulation results for Actros

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

Figure 13 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.

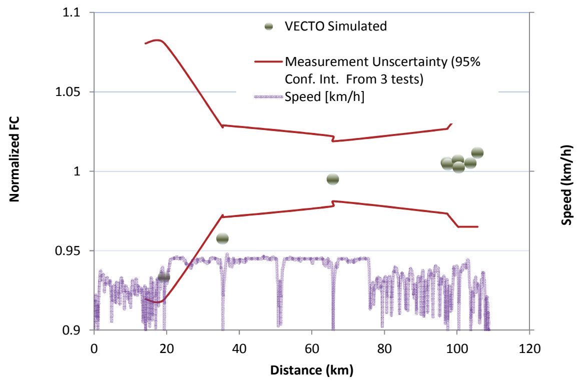

Figure 12: Normalized simulated fuel consumption over distance from start (1=fuel consumption measured during reference test) for Actros. Greed dots correspond to simulation results while red lines indicate the measurement uncertainty on a 95% confidence interval (±2σ). The purple trace indicates the speed over distance trace of the vehicle.

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.

Sensitivity analysis

A sensitivity analysis was performed to determine the influence of variations of VECTO input parameters on the fuel consumption results. The following parameters were used:

- Air drag parameter ±3%
- Rolling resistance ±0.3 kg/t
- Transmission and axle loss maps ±0.3 Nm
- Fuel consumption map

These parameters were varied in the range of the expected accuracy of the underlying measurement procedures (95% confidence interval) to evaluate the overall accuracy and identify possible insufficiencies of the testing methods.

For the fuel map two different scenarios were considered:

a) *"Worst case" tolerance for measurement quantities according to the ECE R49.06 regulation*
The fuel map was varied according to the measurement requirements of the EURO VI emission type approval test.

b) *Tolerances according to test equipment standards*
In this case the fuel map was varied in the measurement tolerance range of state-of-the-art engine test equipment.

In both scenarios all map parameters (engine speed, torque and fuel consumption) were varied in order to have the maximum effect on fuel consumption.

The analysis was conducted with three different vehicles:

- 4x2 Rigid Truck, 12t max. GVW
- 4x2 Tractor & Semitrailer, 40t max GVW
- 6x2 Coach, 24t max GVW

Each vehicle was modelled in VECTO based on typical vehicle specifications for each vehicle class. For the simulations the default class-dependent declaration mission profiles were used.

Results
Air drag and rolling resistance variations showed an influence of up to ±1.5% on the fuel consumption. Considering the complexity of the measurement procedures and the influence of environmental conditions (road surface, rain, snow) this accuracy is regarded as sufficient.

Variation of the transmission and axle loss maps had no significant effect on the results.

For the fuel map, however, it was shown that the "Worst case" according to ECE R49.06 had very high influence. Figure 13 shows the results for both fuel map scenarios for the 40t Long Haul Truck in both declaration mission profiles. (+) and (-) indicate the two variations with the maximum effect on fuel consumption for each scenario.

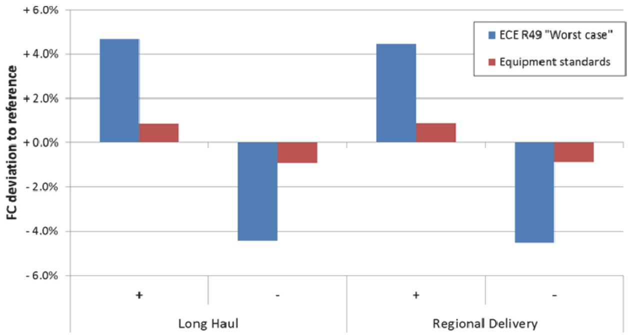

Figure 13: Comparison of the "ECE R49 worst case" and "test equipment tolerances" scenario for the 40t long haul truck

The ECE R49.06 tolerances cause variations in the fuel consumption results of ±4.5% in contrast to the "test equipment standards" scenario with ±1.2%.

Conclusions – Future activity

Simulation tools, and in the particular case VECTO, can reproduce real world CO_2 and fuel consumption performance of HDVs with satisfactory accuracy. In this exercise and for the categories tested, the simulated fuel consumption of on-road operation was calculated roughly 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%), it is concluded that a future certification approach for HDVs can be based on vehicle simulation tools.

A sensitivity analysis of input parameters showed that most component measurement tolerances provide good accuracy, with the sole exception being the engine measurement. The tolerances demanded by the EURO VI emission type approval are not adequate for fuel consumption considering modern equipment tolerances. However, this analysis only shows intermediate results as the test procedure and component tests are still in development.

The findings of this study suggest that a simulation based certification approach for heavy duty vehicles is feasible. Analysis of different simulation scenarios showed that the declaration method currently under development, although not finalized, can provide results that are representative of the real world performance of HDVs, if 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 verify this number.

The European Commission will continue to support this work in the following years aiming to establish a first simulation based certification scheme by 2017 for delivery trucks, the HDV category that accounts for the majority of the CO_2 emissions from HDVs. Additional vehicle categories are expected to follow at a later stage. On the technical side, important improvements which should take place until the implementation of the certification include, drafting of detailed simulation approaches for certain vehicle components and technologies (e.g. automatic gearboxes, driver aids, auxiliaries etc), development of methods to produce the respective input data and further development and optimization of the VECTO simulator.

References

ACEA (2013). Evaluation of VECTO tool. J. D. Clima, ACEA report communicated to the European Commission.

AEA-Ricardo.(2011,Reduction and Testing of GHG emissions from Heavy Duty Vehicles,Final Report,http://ec.europa.eu/clima/policies/transport/vehicles/docs/ec_hdv_ghg_strategy_en.pdf)

AVL (2014). AVL KMA Mobile Fuel Measurement System. WEB.

Clima, D. (2014). "Working document for the methodology drafting for the CO2 monitoring of HD vehicles."

EC (2011). "WHITE PAPER - Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system " COM(2011) 144 final.

Fontaras, G., M. Rexeis, P. Dilara, S. Hausberger and K. Anagnostopoulos (2013). "The Development of a Simulation Tool for Monitoring Heavy-Duty Vehicle CO2 Emissions and Fuel Consumption in Europe." SAE Technical Paper 2013-24-0150.

Fontaras, G., M. Rexeis, S. Hausberger, A. Kies, J. HAMMER, L.-E. Schulte, K. Anagnostopoulos, U. Manfredi, M. Carriero and P. Dilara.(2014,Development of a CO2 certification and monitoring methodology for Heavy Duty Vehicles – Proof of Concept report, http://publications.jrc.ec.europa.eu/repository/handle/111111111/30495)

Franco, V.(2013,Comparison of EU and US models for the simulation of HDV fuel efficiency ICCT report,

Kousoulidou, M., G. Fontaras, L. Lonza and P. Dilara (2013). "Review and evaluation of emission models and vehicle simulation tools." JRC Publication 78179 DOI:10.2790/74085 (print), 10.2790/73957 (online).

Lee, D. and D. Anderson.(2013,Medium- and Heavy-Duty Vehicle Validation,FY 2013 Annual Progress Report,

Luz, R., M. Rexeis, S. Hausberger, D. Jajcevic, W. Lang, L. E. Schulte, J. Hammer, L. Lessmann, M. v. Pim, R. Verbeek and H. Steven.(2014,Development and validation of a methodology for monitoring and certification of greenhouse gas emissions from heavy duty vehicles through vehicle simulation,Final Report CLIMA.C.2/SER/2012/00044, http://ec.europa.eu/clima/policies/transport/vehicles/heavy/docs/final_report_co2_hdv_en.pdf)

Sharpe, B. and D. Lowell (2012). "Certification Procedures for Advanced Technology Heavy-Duty Vehicles: Evaluating Test Methods and Opportunities for Global Alignment." SAE Technical Paper 2012-01-1986.

TU Graz, T., 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,

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