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Assessment of the monitoring methodology for CO_2 emissions from heavy duty vehicles

Pilot phase test-campaign report and analysis of the ex-post verification options

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Title: Assessment of the Monitoring Methodology for CO_2 Emissions from Heavy Duty Vehicles

Abstract

Following a request from DG-Clima and DG-GROW, JRC launched a test-campaign in order to investigate the validity, accuracy and plausibility of the methodology proposed for the verification of the certified CO_2 emissions from Heavy Duty Vehicles (aka ex-post verification methodology). In addition scope of the test campaign was to demonstrate the representativeness of the CO_2 emissions calculations made by the official simulator (VECTO) by comparing against the actual performance of vehicles. Experiments were conducted on four Euro VI trucks, both on the chassis dyno and on the road with the aim of understanding the advantages and disadvantages of different approaches proposed. Two main verification approaches were investigated, steady state measurements in chassis-dyno / controlled conditions, and measurements under transient conditions on chassis-dyno and actual on-road operating conditions. The official simulation software (VECTO) was used for simulating the operation of vehicles under the different test conditions. The key conclusion of the test campaign is that an ex-post verification method which is based on transient, on-road tests is possible for trucks and comes with the advantage that it could potentially cover also other vehicle types which are difficult to be validated under steady state conditions in a laboratory or on a test track under controlled conditions. However, there is a clear need to work on the details of the test protocol to be finally implemented, define boundary conditions for transient tests on road, and establish the necessary acceptance and rejection margins for any such validation. Finally, additional testing is necessary in order to calculate accurately any systematic deviation between the officially reported, simulated, CO_2 values and those actually occurring in reality. VECTO results should be periodically controlled and assessed in order to make sure that its CO_2 estimates remain representative and minimize the possibility that discrepancies will occur in the future between the officially reported and actually experienced fuel consumption.

Contents

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- Daimler (Michael Berner, Ralf Krukenberg)
- Scania (Henrik Wentzel)
- Volvo (Jan Melin)

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Executive Summary

Policy context

The European Commission has been working on the preparation of a new regulatory initiative for monitoring CO_2 emissions and fuel consumption from Heavy Duty Vehicles (HDV) in Europe. The new methodology is based on a combination of component testing and computer simulation of the vehicles' fuel consumption. Dedicated software simulator has been developed for this purpose (Vehicle Energy Consumption calculation Tool – VECTO). In parallel a series of new component testing protocols and methods were also developed in order to measure vehicle components and provide the necessary input data for running VECTO. As a result the final vehicle CO_2 emissions are calculated based on data received from components testing and computer simulations without the physical need of the complete vehicle. This method allows specific CO_2 emission values to be attributed to each vehicle, provides the necessary flexibility to the vehicle manufacturers as the HDV market is highly differentiated with limited common features between different vehicle models and reduces the costs of vehicle certification. However, some form of verification of the final CO_2 result and the quality of input data used in the simulations was deemed necessary by various stakeholders and European Member States who requested the development of an appropriate verification procedure to be applied randomly on complete vehicles after the certification processes has taken place (ex-post verification).

Initially two possible verification approaches were proposed, one foreseeing steady state (SS) tests under controlled conditions (chassis dyno or test-track testing) and a second foreseeing transient testing under on-road conditions similar to – but not the same as – the in-service-conformity testing. Following a request from DG-CLIMA and DG-GROW, JRC launched a test-campaign in order to investigate the validity, accuracy and plausibility of each one of the two methodologies. In addition JRC was ask to produce data that demonstrated the representativeness of VECTO’s fuel consumption calculations by comparing simulation results against the measured fuel consumption of the vehicles. Experiments were conducted on four Euro VI trucks, both on the chassis dyno and on the road with the aim of understanding the advantages and disadvantages of the different approaches proposed.

Key conclusions

The key conclusion of the test campaign is that an ex-post verification method that is based on transient, on-road tests is plausible for trucks and comes with the advantage that it could potentially cover also other vehicle types that are difficult, if not impossible, to be measured under steady state conditions in a laboratory or on a test track. The steady state option presented other disadvantages such as higher costs, difficulty to be reproduced without the involvement of the vehicle manufacturer and in certain situation lower stability and repeatability. In order to introduce a transient ex-post verification method in the HDV certification scheme there is a clear need to work on the details of the respective test protocol, define clear boundary conditions for the tests and establish the necessary acceptance and rejection margins for any such validation. With regards to VECTO’s stability and capacity to produce realistic results, no new major issues were identified and VECTO performed within the expected, previously reported margins. A beta-version of the tool was used in the study so an additional assessment is advisable once the official release of the tool is made. Finally, additional testing is necessary in order to calculate accurately any systematic deviation between the officially reported, simulated, CO_2 values and those actually occurring in reality. VECTO results should be periodically controlled and assessed in order to make sure that its CO_2 estimates remain representative and minimize the possibility that discrepancies will occur in the future between the officially reported and actually experienced fuel consumption.

Quick guide / Experimental

Tests were conducted at the facilities of JRC (VELA 7). Four vehicles were tested (all of them N3 category) equipped with state of the art exhaust after treatment systems like Diesel Particulate filters (DPF) and Selective Catalyst Reduction of NO_x (SCR). All tested vehicles were Euro VI certified. The vehicles were tested in the laboratory over the ACEA Regional Delivery cycle (RD) and the World Harmonized Vehicle Cycle (WHVC). Furthermore, steady state points at various load and rpm pairs were measured according to the provisional SS Cycle (SiCO test). Finally, on-road tests were performed over a 200 km route which included distinct urban, rural, and motorway parts.

An AVL i60 AMA 4000 system was used for the analysis of pollutants emissions. A Heated NDIR (Non-Dispersive Infrared sensor) was used for CO_2 emissions measurement and the subsequent calculation of the fuel consumption. For the chassis dyno tests the climatic room was adjusted at the temperature of 20°C. CO_2 was measured downstream of the exhaust after-treatment system of the truck. The calculation of the engine work output over each sub-cycle was based on the instantaneous engine torque and rpm values which were recorded via the vehicle's OBD (On-Board Diagnostics) system. The calculation of the wheel work output (or cardan shaft work output) over each sub-cycle was based on the instantaneous wheel torque values (or cardan shaft torque values) measured by a Kistler wheel-rim torque measurement system, or in the case of one of the vehicles, with a cardan-shaft mounted torque meter. Further to the standard instantaneous CO_2 measurement, instantaneous fuel consumption was measured also with an AVL KMA Mobile fuel flow meter for crosschecking purposes. However, this method was not always applied due to certain limitations imposed by the fueling system of two of the tested trucks.

At least five repetitions of each cycle were conducted, of which at least three were considered for a robust statistical analysis of the results. Tests were performed during the same day but also over different days. Tests were performed always under warm start conditions under the following sequence: WHVC, RD, and SiCO points. WHVC and RD were tested in order to evaluate VECTO’s capability to reproduce also transient cycles in the lab. At least three on-road tests were performed for all vehicles.

All FC values provided in the report are normalized to the average FC of each vehicle separately. Thus, normalized FC values of different vehicles cannot be compared to each other by any means.

Results Analysis - Main findings

The ex-post verification exercise was conducted in two phases:

- The experimental phase which took place between February and July 2016 in JRC and involved testing of four Euro VI trucks in the laboratory and on-road.

- The simulations phase, which took place between May and November 2016, during which simulations were performed by each individual OEM following the guidelines of the JRC.

Four major OEMs participated at the exercise (in alphabetical order DAF, Daimler, Scania, and Volvo) by providing a truck along with the necessary technical support. The manufacturers performed the simulations after tests had been finalized by the JRC without knowing the fuel consumption / CO_2 emissions results. Simulation results were then communicated to the JRC who performed an independent comparison between the results of the simulations and those of the measurements. At a final step conclusions were communicated to the respective OEM. The findings of the main evaluation phase can be summarized to the following:

Steady State testing in the laboratory

- Steady state testing (SiCO test) proved to be satisfactorily repeatable in the laboratory in terms of fuel consumption, particularly when testing medium and high load points (i.e. power at the wheel or shaft >100 kW). Low load points (i.e. power at wheel or shaft <50 kW) proved to be less repeatable and thus more unstable compared to medium and high load points. This observation was confirmed by all OEMs and it needs to be considered seriously as an important share of the fuel consumption occurs over low load points, particularly in the cases of smaller trucks and other types of HDV operating in urban and rural conditions. During on-road low load operation occurred during a substantial part of the trips, therefore they should not be completely neglected when performing CO_2 emissions validations.
- A good agreement between measured and simulated fuel consumption values over medium and high loads was observed (deviations between measured and simulated specific fuel consumption (g Fuel/kWh) was always lower than 2%) with two of the trucks tested. This was not the case for low load points (i.e. power at wheel or shaft <50 kW) where in some cases the deviation between measured and simulated specific fuel consumption reached 4%. Vehicles #3 and #4 demonstrated generally higher deviations between measured and simulated fuel consumption values, regardless the tested load. Further investigation is required to understand the higher deviations found for these two vehicles.
- Apart from the issue with low load points this test campaign revealed other drawbacks related to the SiCO test methodology. First of all, it is very difficult to cover the full engine and gearbox map with only 12 (or even 18) steady state points. Furthermore, it is not possible with one single test protocol to cover the full range of HD vehicles (trucks, buses, coaches, etc.). Finally, this type of testing requires expensive and difficult to maintain equipment, both when tests are performed in the lab (expensive chassis dyno installations) and when they have to be performed on road (special braking trailers, dedicated testing facilities, possibly longer duration of testing due to varying weather conditions).

Transient testing in the laboratory

- In lab tests presented very good measurement repeatability (i.e. coefficient of variation for three fuel consumption measurements <2%) over the Regional

Delivery cycle. Higher deviations were observed with the WHVC cycle for almost all vehicles (coefficient of variation close to 5%). Compared to Regional Delivery, WHVC speed profile includes many more braking events and is characterized from generally lower speeds and lower load points. This could explain the lower repeatability of WHVC. Finally, specific fuel consumption was found to be higher over the WHVC than the Regional Delivery probably due to the more transient nature of WHVC.

- A satisfactory agreement was observed between measured and simulated fuel consumption over the Regional Delivery tests with the deviation between tests and simulations being generally lower than 3% and only once reaching up to 5%. VECTO P_{Wheel} mode (hereafter mentioned as VECTO SiCO mode) provided more precise and in several cases also more accurate results compared to the VECTO Engineering mode (whenever both modes were examined over the RD cycle). This was an expected finding as the SiCO mode generally exhibits lower uncertainties, the origin of which relates to the uncertainties in the estimation of the vehicle's road loads (air drag and rolling resistance) under different operating conditions, a factor which is more pronounced in real world driving but is also present during chassis dyno testing. WHVC simulations were less accurate compared to the RD ones, regardless the vehicle tested. In general, it could be concluded that VECTO is capable of providing reliable fuel consumption estimates for the in-lab tests, over different transient cycles, exhibiting, however, a slightly higher uncertainty compared to the SiCO results.
- There are various drawbacks related to transient testing method in the laboratory. There are several difficulties for the driver to reproduce braking events over transient cycles and specifically over a highly transient cycle such as the WHVC (or potentially any of the lower speed cycles included in VECTO). Despite that the operating points for the engine and the gearbox are closer to those experienced over real world driving conditions, they do not cover the full range of the engine/gearbox maps. In addition, some vehicles currently, and more vehicles in the future, are equipped with sensors or GPS systems that define the operation of certain components (e.g. gearbox) according certain external parameters (under which conditions the vehicle operates or is expected to be operating). The effect of such systems is totally excluded when testing on a dyno (i.e. vehicle at stand still). Furthermore, it is not possible with one single test protocol to cover the full range of HD vehicles (trucks, buses, coaches, etc.). There is a need for expensive and difficult to maintain equipment (chassis dyno, special braking trailers, etc.). Overall, it seems to be an unfavorable compromise between steady state and on-road tests as it doesn't solve the issues related to the other two methods.

On-road testing

- Very good repeatability was observed in the measurements of specific fuel consumption over on-road tests, regardless the truck tested. The coefficient of variation of specific fuel consumption measurements over three repetitions was always lower than 1.5%. This result is somewhat surprising since these tests were known to be more uncertain than the ones on the chassis dyno and difficult to repeat with high precision.

- Overall, a good agreement between measured and simulated specific fuel consumption values was observed over on-road tests with the deviation never exceeding <5%. When the wheel rims were used for the measurement of the torque at wheel the deviation between measured and simulated specific fuel consumption did not exceed 3% for vehicles #2, #3 and #4, while in the case of vehicle #1 it was found to be close to 5% due to a drift of the torquemeter installed at the cardan shaft. VECTO SiCO mode proved to be more precise in simulating measured fuel consumption values compared to Engineering mode. Overall, it seems that VECTO is capable of providing reliable results over on-road tests. However, differences among different VECTO modes should be further investigated.
- On-road tests seem to be a good solution for the ex-post verification procedure as they overcome most of the drawbacks related to the laboratory-based testing methodologies. First of all, a wider area of the engine and gearbox maps is investigated as the truck operates under real world conditions. A final testing methodology could be adopted to cover even a wider range of HD Vehicle maps, by for example introducing testing with different loadings (e.g. different vehicle payloads). Finally, on road tests overcome the need for very expensive to purchase and maintain equipment (chassis dyno, special braking trailers, etc.).
- Still, as in the previous options (SiCO test, In-lab transient cycle tests) it is necessary to include in an on-road verification test, torque measurement systems which have a certain cost. However, such systems are also used for the measurement and definition of the vehicle air drag value (CdxA) according to the respective test protocol.
- Regardless the testing methodology, a better agreement between measured and simulated specific fuel consumption values was observed when using the wheel rim torque measurement systems as opposed to the cardan shaft torque measurement system. This observation became more obvious over on-road tests due to their longer duration compared to laboratory tests. Whether this behavior occurred due to the characteristics of the specific cardan shaft sensor, or could it be a generalized behavior, remains an open point that reaches beyond the scope of the study.

Related and future JRC work

Based on the results of the Ex-Post validation phase, the Graz University of Technology (TUG) will conduct an error propagation analysis in order to confirm the findings and conclusions of JRC. Afterwards, TUG may jointly proceed into drafting a first version of the ex-post verification test protocol. JRC will support/participate in the further steps.

1 Introduction

The European Commission published in 2011 its "White Paper on transport" (2011) with the aim of providing a pathway to increase the sustainability of the transport system. In this document the European Commission suggests that reducing vehicle fuel consumption will have a positive effect on overall CO_2 emissions. However, without a robust CO_2 and fuel consumption monitoring methodology it is not feasible to achieve neither short-term policy planning nor any additional relative initiative. A robust CO_2 and fuel consumption monitoring method should reflect the real world performance of the vehicles as well as the comparative advantages of different vehicle models and technology packages available in the market. This way necessary and useful information will arrive to the end user and will allow the introduction into the market of vehicles with lower fuel consumption. The Commission's European Strategy for Low Emission Mobility, published in July 2016, reiterates the importance of a low carbon transport sector and sets out an overall vision built on three pillars: moving towards zero-emission vehicles; low emission alternative energy for transport and efficiency of the transport system. Robust emissions monitoring is necessary for the successful deployment of initiatives across all three pillars. The aim of the Commission according to the European Strategy for Low Emission Mobility is to speed up analytical work on design options for CO_2 emission standards for HDVs such as lorries, buses and coaches and is planning to launch a public consultation to prepare the ground for a proposal during this mandate (EC, 2016).

Heavy-duty vehicle emissions are not yet monitored in a commonly agreed way in Europe, while at the same time until recently there was no standardized and consistent method for quantifying such emissions. The acceptance of the draft HDV CO_2 certification legislation in May 2017, initially covering Heavy Duty Trucks, and the respective simulation-based CO_2 quantification methodology, is an important first step in addressing this issue and is expected to contribute towards lowering CO_2 emissions. Still there is an absence of consistent CO_2 emissions monitoring; the EC has initiated a series of projects with the aim of establishing a comprehensive, standardized and accurate method to quantify and report CO_2 emissions from HDVs. The issue of energy efficiency of HDVs is important also for other policy instruments. For instance, the public procurement legislation in Europe requires that within the criteria set for the procurement of vehicles, energy efficiency and environmental performance specifications have to be taken into consideration.

Initial studies and feedback received from involved stakeholders suggested that the approach that best fits the characteristics and particularities of the HDV sector is founded on a combination of component testing and computer simulation (AEA-Ricardo, 2013). Similar approaches have already been adopted by the US and Japan. Measurement of vehicles or their components is fundamental for building accurate and reliable models and it is foreseen in all certification approaches already established. At the time of writing of this report, vehicle simulation software (Vehicle Energy consumption Calculation Tool, or VECTO) is being developed to be used for the purpose (Fontaras et al. 2013), while its beta version has been tested both by the EC and individual OEMs regarding its capacity to calculate representative CO_2 emissions. In this model total fuel consumption is simulated based on vehicle longitudinal dynamics from the input data on the vehicle and engine characteristics. Equally important are the established test protocols for measuring individual vehicle components and producing the required input data for running the simulations (EC, 2017). The plausibility of such a simulation-based approach was assessed in an extensive experimental campaign conducted by the EC's Joint Research

Centre (JRC). This study provided detailed experimental results for supporting the plausibility of the simulation-based approach and its results have been described elsewhere (Fontaras et al. 2013).

It should be noted that in the adopted simulation-based procedure, the final vehicle CO_2 emissions are calculated based on data received from components testing and computer simulations without the physical need of the complete vehicle. On one hand the method allows specific CO_2 emission values to be attributed to each vehicle, providing the necessary flexibility to the vehicle manufacturers as the HDV market is highly differentiated with limited common features between different vehicle models and reducing the costs of vehicle certification. However, some form of verification of the final CO_2 result and the quality of input data used in the simulations was deemed necessary by various stakeholders and European Member States for transparency, quality control and trust-building reasons. As a result it was decided to develop an appropriate verification procedure to be applied on complete vehicles after the certification process has taken place (ex-post verification).

Initially two possible verification approaches were proposed: one foreseeing steady state tests at controlled conditions (chassis dyno or test-track testing); the second foreseeing transient testing under on-road conditions similar to but not the same as the in-service-conformity testing. Following a request from DG-CLIMA and DG-GROW, JRC launched a test-campaign in order to investigate the validity, accuracy and plausibility of each one of the two methodologies. In addition JRC was ask to produce data that demonstrated the representativeness of VECTO's fuel consumption calculations by comparing simulation results against the measured fuel consumption of the vehicles. Experiments were conducted on four Euro VI trucks, both on the chassis dyno and on the road with the aim of understanding the advantages and disadvantages of the different approaches proposed.

This report summarizes the outcome of the abovementioned experimental test campaign and attempts to provide insight with regards to the advantages and disadvantages of the two different verification methods. In addition the data retrieved from the measurements come to supplement those of the previous test campaigns regarding the capacity of VECTO and the proposed approach to capture the CO_2 emissions of vehicles. Experiments were conducted on four Euro VI long haul trucks both on the chassis dyno and on the road. The VECTO simulation tool was used for simulating the tests.

2 Experimental methods

Measurements took place between January and September 2016. Parts of the tests were combined with other projects concurrently running at the JRC after prior coordination and agreement with the respective OEMs[1]. In this report only the Ex-Post validation test campaign results will be presented and discussed.

All tested HD vehicles were Euro VI. Measurements included tests on the chassis dyno at steady state conditions and at dynamic conditions and on the road following real-world driving patterns. Detailed descriptions of the vehicles, protocols and test conditions are provided in this chapter.

2.1 VELA 7 facilities and setup

Chassis dyno measurements were performed at the Heavy Duty Chassis dynamometer of the Vehicle Emissions Laboratory (VELA 7) of the European Commission’s Joint Research Centre (JRC).

The two-roller chassis dynamometer (Zoellner GmbH, Germany) has been designed to host even 4-wheel drive HDVs of up to 30 t in weight, 12 m in length, and 5 m in height. HDVs of 2 axles can also be accommodated. Maximal test speed is set at 150 km/h. The application of pull-down up to 20 kN in order to avoid slipping of the tyres is also feasible. The test cell can be conditioned in temperatures between -30°C and +50°C and relative humidity between 15% and 95%, providing thus the ability to test vehicles under extreme conditions. All laboratory tests were conducted at 20°C and 50%. 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. Tests were usually performed with an air flow of 100 m^3/min, except for some demanding high load steady state points which were performed with maximal air flow. 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 regardless the fuel used. Figure 1 provides an overview of the VELA 7 facilities.

In certain cases in addition to CO_2 other gas pollutants were measured (i.e. THC, CH_4, CO, NO_x). An AVL i60 AMA 4000 system was used for the analysis of gaseous emissions in the laboratory. A Heated Flame Ionization Detector (HFID) was employed for measuring exhaust gas concentrations of THC and CH_4. A Heated Non-Dispersive Infrared sensor (NDIR) was used for CO_2 and CO emissions. Finally, a Heated ChemiLuminescence Detector (CLD) was employed for the measurement of exhaust NO_x. Pollutants were measured downstream of the exhaust aftertreatment system of each truck. All fuel consumption calculations in the laboratory were performed based on the CO_2 measurements from the AMA analyzer unless mentioned otherwise. Figure 2 shows the instrumentation used for the purposes of the study.

[1] During the period from January to September 2016 different HD related projects were running concurrently at VELA 7 facilities. In addition to the Ex-Post validation exercise, certain tests for the PN PEMS and the Cold Start projects were conducted. Results from these two test campaigns have been published in another JRC Science for Policy Report (Giechaskiel et al. 2016). Furthermore, some tests for the needs of the PMP sub23 project were performed.

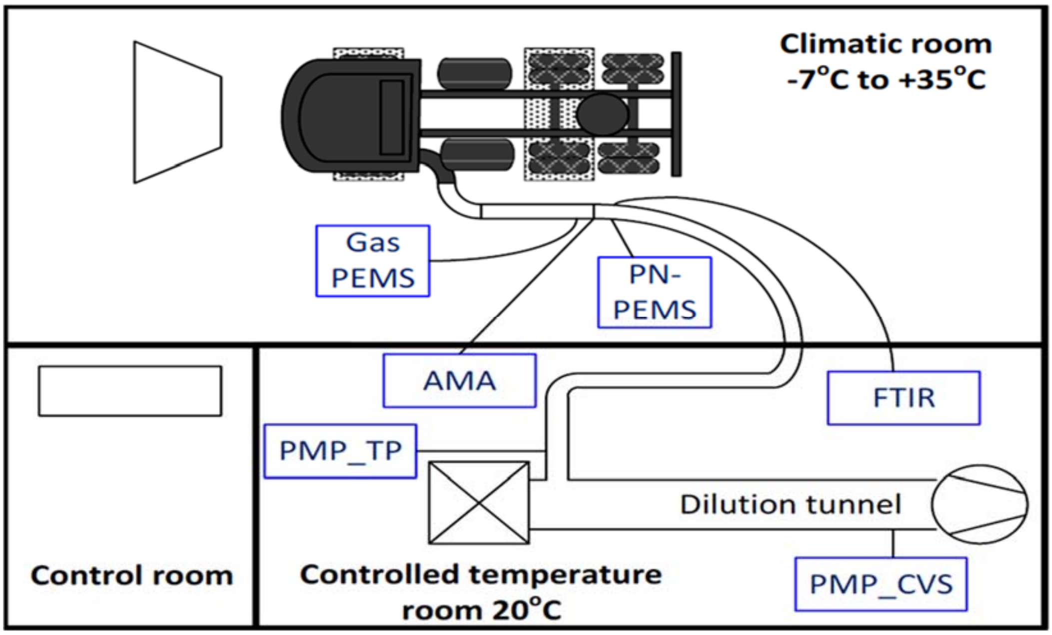

Figure 1: VELA 7 facilities

A Gas-PEMS system was used both in the lab and on-road. The reason for using gas-PEMS in all tests was to maintain a common reference instrument for all vehicles and all test conditions. All other CO_2 / future consumption signals were compared against this common reference. A Semtech-DS PEMS system was used, manufactured by Sensors Inc., and it consisted of tailpipe attachment, heated exhaust lines, an exhaust flow meter (EFM) (4'' or 5'' depending on the vehicle tested), exhaust gas analysers, data logger to vehicle network, a global positioning system (GPS), and a weather station for ambient temperature and humidity. All data were recorded at a frequency of 1 Hz and the whole system added further ~100 kg of instrumentation to the vehicle. An independent power generator was used to produce current for the needs of the PEMS. The Semtech DS measured exhaust gas concentrations of unburned hydrocarbons (THC) by HFID, carbon monoxide (CO) and carbon dioxide (CO_2) by a NDIR, and nitrogen monoxide (NO) and nitrogen dioxide (NO_2) by a non-dispersive ultraviolet sensor (NDUV). The oxides of nitrogen (NO_x) could be calculated by the sum of the concentrations of NO and NO_2. The measurement principles and accuracy from the Semtech DS were in-line to those described by current legislation for this type of testing. As a standard procedure, test runs preparation included routine calibration of pollutant analysers (zero and span of gases). All fuel consumption calculations on-road were performed based on the CO_2 measurements from the PEMS system while is some cases on board fuel measurement systems were used for comparison purposes. No gaseous pollutants results will be presented in this report as it is out of the scope of the current exercise.

Mobile fuel flow meter was not employed for measuring instantaneous fuel flow in all tests due to functional problems. In all cases the on-board fuel flow indication provided by the vehicles was used for recording instantaneous fuel consumption. However, fuel consumption results were reported based on the gas PEMS system which was used with the 5'' Exhaust Flow Meter (EFM) for vehicles #1, #2 and #4 and with the 4'' EFM for vehicle #3. A validation against instantaneous CO_2 data recorded during the lab tests was performed by installing the gas PEMS system also in some laboratory measurements. The gas PEMS system in the lab provided highly comparable readings to the AMA system (<2% difference) especially when transient cycles were compared.

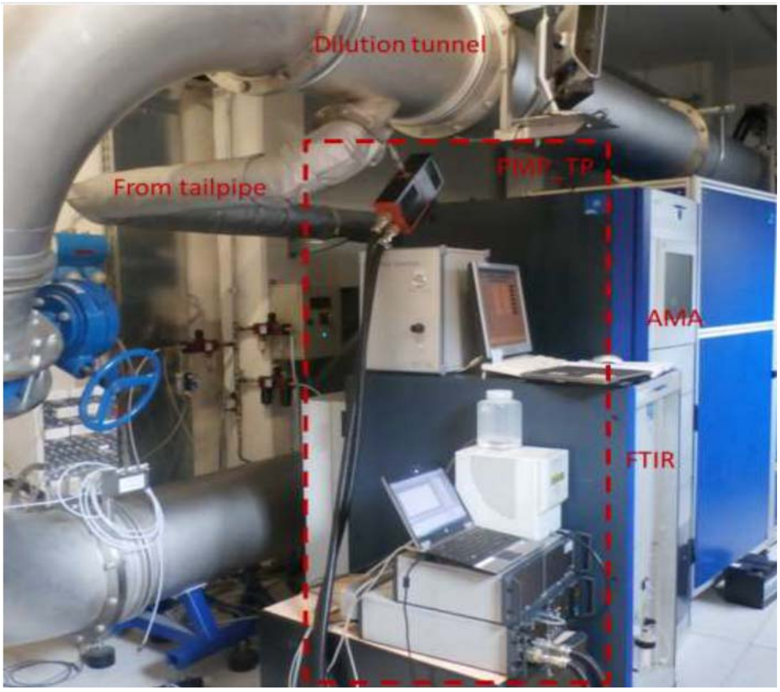

Figure 2: Setup of the instrumentation in the controlled temperature dilution tunnel room

2.2 Test vehicles

Four vehicles were employed for the purposes of the present study. Three long haul vehicles and one regional vehicle were selected. Some generalized properties of the vehicles are provided in Table 1. All vehicles were provided by the respective OEMs in their standard operating. Figure 3 demonstrates vehicles tested in VELA 7 and on-road. The numbering of the vehicles (i.e. #1 to #4) does not correspond in any way to the presentation of the vehicles in Figure 3.

Table 1: Main vehicle characteristics and main input data origin

Characteristic	Range of Values
Engine Displacement [cm^3]	7700 – 12900
Rated Power [kW]	240 – 355
Rated Torque [Nm]	1224 – 2500
Gearbox	Manual or AMT
Max load [kg]	24,000 – 40,000
Test Mass [kg]	17,000 – 27,000
Emissions Category	EURO VI
Torque measurement	Cardan shaft transducer or Wheel rim torquemeter
Exhaust emissions control	EGR, DPF, SCR

During all tests signals from the vehicles On Board Diagnostic (OBD) port were recorded. The calculation of the engine work output over each cycle was based on the instantaneous engine torque and rpm values which were recorded via the vehicle's ECU (Engine Control Unit). However, this value was not used for the calculation of the specific fuel consumption but only for cross validation purposes.

Vehicle specific fuel consumption was calculated using the loads imposed on the vehicles during the tests. For these calculations the total work output of the driveline system (positive or absolute) was calculated from torque measurement devices installed either at the shaft or at the wheels. This allowed on a second step a better validation of the resistances simulated by VECTO and an assessment of the origin of the inaccuracies in the calculations.

Figure 3: Trucks tested in the climatic room and on-road

2.3 Daily test protocol and test cycles

The daily test protocol in the laboratory consisted of three different types of test cycles that covered from commonly used test cycles to highly dynamic speed-versus-distance cycles. The WHVC (World Harmonized Vehicle Cycle) has been commonly used for emissions study of different types of HDVs, and consist of three very distinct phases, the urban, rural and motorway. The Regional Delivery Cycle (RD) is a distance-based cycle which is considered to provide a more realistic approach for evaluating the fuel consumption performance of a multitude of different HDV without overlooking their optimal performance conditions. Finally, constant speed tests (SiCO tests) with predefined combinations of engine rpm and real time measured torque were executed with the aim of investigating the CO_2 emissions at various engine points.

WHVC is the equivalent of the engine World Harmonized Test Cycle (WHTC) to a vehicle cycle for the chassis dynamometer. The duration of the WHVC test is 1800 s. The first 900 s represent urban driving with an average speed of 21.3 km/h and a maximum speed of 66.2 km/h. This segment includes frequent starts, stops and idling. The following 481 s represent rural driving with an average speed of 43.6 km/h and a maximum speed of 75.9 km/h. The last 419 s are defined as highway driving with average speed of 76.7 km/h and a maximum speed of 87.8 km/h. No slopes were applied in all cases, thus the work of this cycle was different to the type approval work of the WHTC. The speed versus time profile of WHVC is given in Figure 4.

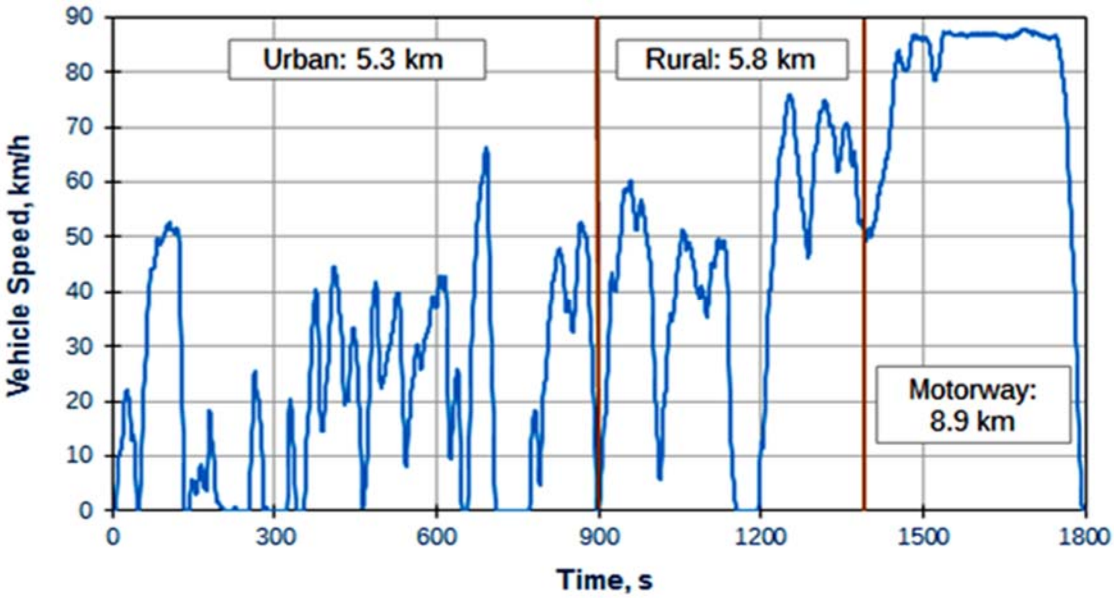

Figure 4: Speed versus time profile of WHVC

Regional Delivery[2] belongs to a group of distance based cycles where the actual speed of the vehicle at any moment in time is produced by the simulator as a function of the vehicle characteristics (weight, resistances, and available power) as well as the modelled behaviour of the driver. Such an approach is considered much more realistic for evaluating the performance of a multitude of different HDV without overlooking their optimal performance conditions. The benefits of various driver aids, which are very common in HDV applications, can also be demonstrated in the distance-based approach. Finally, in order to match realistic conditions more closely, the RDC features additionally the slope as a function of the traveled distance. The RDC has been proposed to be included in the forthcoming CO_2 monitoring and reporting legislation as a representative cycle for rural delivery conditions in Europe. The speed versus distance profile of the RDC is depicted in Figure 5.

[2] The 2016 version of the regional delivery cycle was used in the study

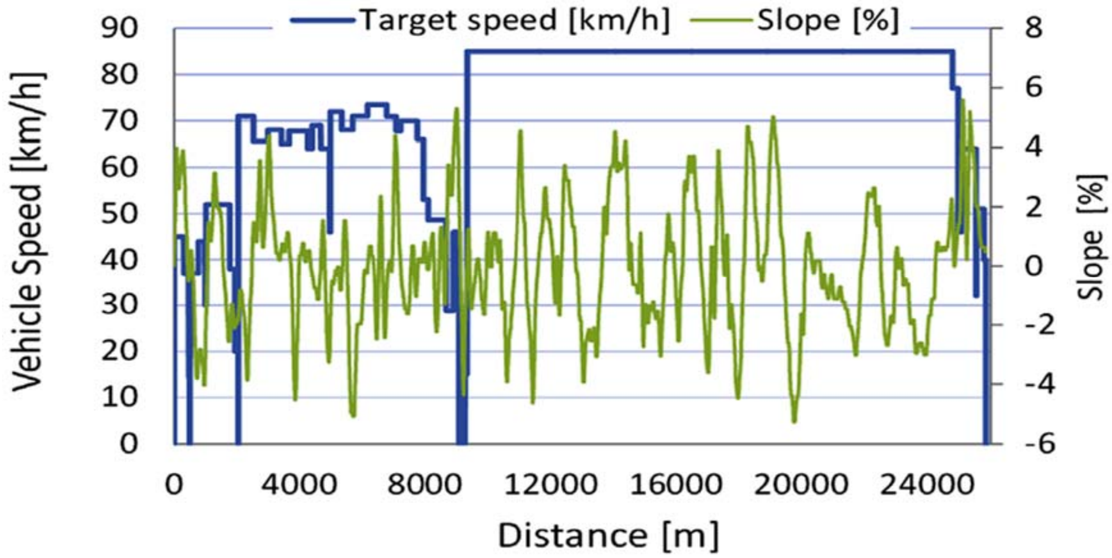

Figure 5: Speed versus distance profile of Regional Delivery

Constant Speed test (SiCO test) with predefined combinations of engine rpm and real time measured wheel (or shaft) torque (predefined test cycle in VECTO consisting of constant speeds for optional later validation of the CO_2 result produced for a HDV) were also performed with the aim of investigating the CO_2 specific emissions at various engine load points. For each vehicle a different sequence of test points was applied depending on its characteristics (i.e. rated power, engine displacement, etc.). At least 15 load points were examined for each vehicle. Warm-up of the vehicle for at least 1h at high load conditions in order to achieve a minimum of 60°C for the axle and 75°C for the transmission oil was required. A repetition of each point is defined as a minimum of 60s after stabilization phase. Tests are performed with all auxiliaries being switched off (i.e. A/C switched OFF, data with Air Compressor Status ON are disregarded). A minimum of 3 repetitions of the points sequence is required for a robust statistical analysis. Figure 6 shows the applied constant speed profile of engine rpm versus torque for vehicle #2.

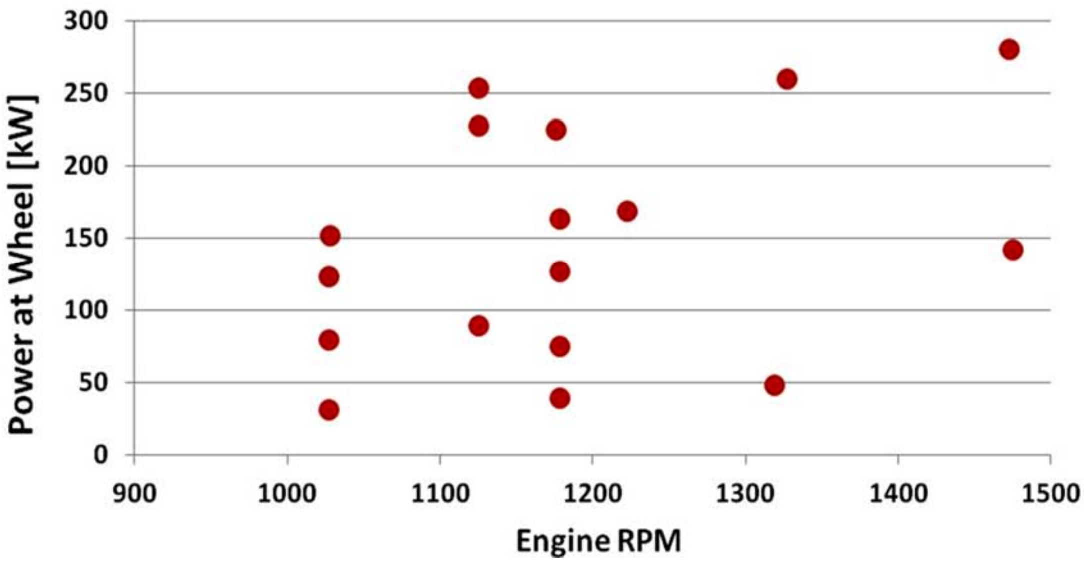

Figure 6: Example of a constant speed profile of engine rpm vs. torque for vehicle #2

Figure 7: Route for on-road tests performed. Red line - Motorway; Blue line - Urban & Rural

On-road tests around the JRC site were performed to simulate real-world emissions. A mixed route of total distance of approximately 200 km which consists of urban, rural and highway parts was driven (Figure 7). The highway part accounts for approximately 150 km allowing thus to simulate the real world operating conditions of long-haul trucks. In Figure 7 the highway part has been spotted with the red line, whereas urban and rural parts are shown with the blue line. Figure 8 shows the speed profile of vehicle #2 over the described route.

The scope of on-road tests was to obtain a mix of operating conditions similar to those of the chassis dynamometer tests. Also there was a need for investigating parameters such as the repeatability of the tests and the agreement between measured and simulated values since on-road tests were considered to be less repeatable compared to laboratory tests.

The route's statistics with the four vehicles are summarized in Table 2. A PEMS compliant trip would stop at around time 6000s. However, it was decided to extend the measurement period throughout the whole trip for the purposes of this project. The highest deviations were observed at the rural phase where in some cases vehicles exceeded 70 km/h, thus attributing the part of the trip to the motorway phase. All vehicles were tested at least three times except for vehicle #4 which was tested only twice due to time restrictions.

Table 2: Driving phase distributions of on-road trips

Speed Classification	Share in total trip duration
Low Speed <50 km/h [~Urban]	23-27%
Medium Speed 50-70 km/h [~Rural]	4-15%
High Speed >70 km/h [~Motorway]	60-69%

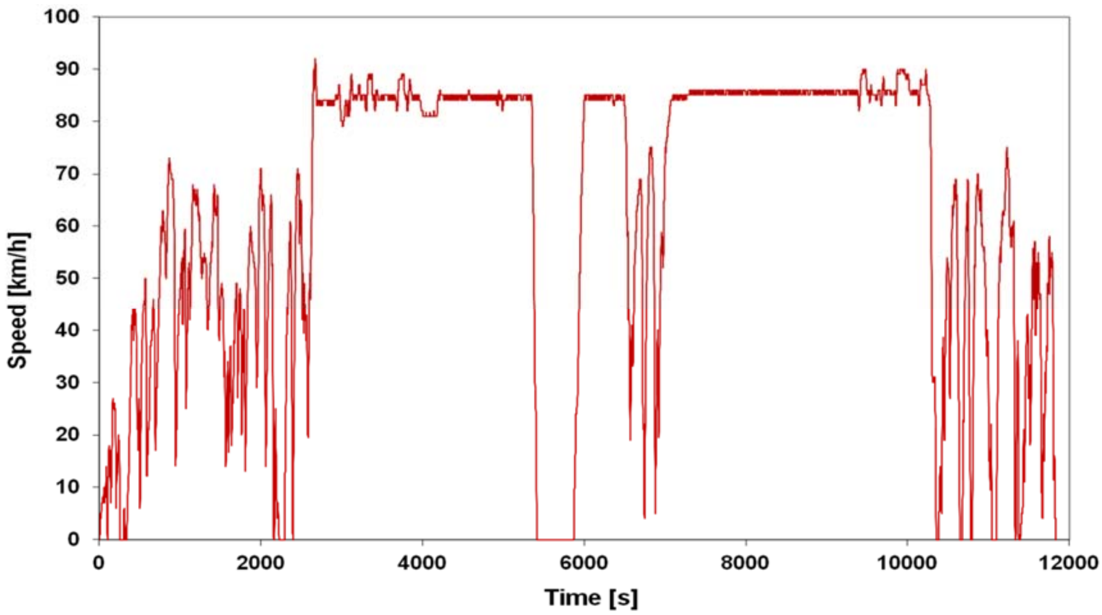

Figure 8: Speed profile of vehicle #2 during one typical on-road test

2.4 Vehicle simulator

The VECTO-simulator is the core component of the proposed methodology. The software simulates CO_2 emissions and fuel consumption based on vehicle longitudinal dynamics using a driver model for simulation of target speed cycles. The load required by the internal combustion engine is calculated internally in 1Hz steps based on the driving resistances, the power losses in the drive train system, and the power consumption of the vehicle auxiliary units. Engine speed is determined based on a gear-shifting model, the gear ratios, and the wheel diameter. Fuel consumption and CO_2 emissions are then interpolated from an engine fuel/CO_2 map.

Currently, in each timestamp VECTO interpolates the engine fuel consumption based on the simulated engine speed and torque from an engine fuel map measured in steady state conditions at the engine test bed. To overcome the shortcomings introduced by the use of steady state fuel map in for the simulation of transient operating conditions, it is foreseen in VECTO that a correction factor is applied. This correction factor shall be determined based on the quotient of measured fuel consumption in a transient real world cycle (most probably the WHTC) and the simulated fuel consumption for this cycle based on the steady state engine fuel map. More details on the procedure for obtaining the map and the correction function are provided by Luz et al. [2014].

The main characteristics of the current VECTO version can be summarized in the following list:

- Backwards-calculating, quasi-stationary longitudinal dynamics model with pre- and post-processing loops (e.g. for time to distance conversions, driving aids and WHVC corrections);
- Time-based or Distance-based cycles (time-steps may have varying duration, distance-steps must be at most 1min length);
- 1 s (1 Hz) Internal and Output time-steps;
- Driving model considers real life driving behavior (e.g. acceleration and breaking curves, gear shifting, coasting);
- Input and output via text-files;
- Implemented as Visual Basic. NET application (Windows);
- Graphical user interface for calculation control and editing of the main input files;
- Declaration mode with locked-values and cryptographic signing of results for certification purposes.

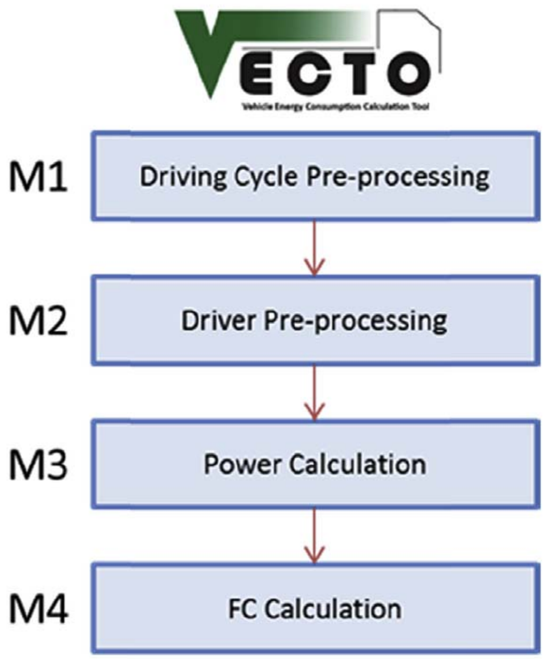

Figure 9: VECTO’s simulation core

The simulation-core is summarized schematically in Figure 9. Additional information about the software and its functionality can be found in Fontaras et al. (2013) and Luz et al. (2014). A series of studies have shown that VECTO performs adequately and in a similar way as other established commercial or regulation oriented simulators Franco et al. (2015), ACEA (2013).

Table 3 briefly describes the available VECTO modes. The official (declaration) mode uses official values and input (as in certification) for all parameters (i.e. mass, road loads, gearbox, axle, engine) as well as constant predefined values for the auxiliaries. Declaration mode was not examined in the current study. The engineering mode uses as input values for mass, road loads and drive cycle those measured by the JRC. Additionally, VECTO considers power losses for gearbox, axle, engine and some of the auxiliaries. Engineering mode was applied in several tests and in particular to those conducted on-road. Finally, the SiCO mode requires the measured values of the torque at wheel or at shaft along with the measured engine RPM. All other input comes from the official gearbox, axle and engine maps. The SiCO mode was applied in all executed tests. VECTO simulations were all run by the respective OEM with data provided by the JRC. Different versions of the tool were used depending on each OEM. The versions used by each OEM are given at the respective results section.

Table 3: VECTO modes description

Test	Mass & Road loads	Gearbox & Axle	Engine	Auxiliaries	Drive Cycle
Declaration mode	Official values and input (certification)	Official values and input (certification)	Official values and input (certification)	Official values and input (certification)	Official values and input (certification)
Engineering mode	JRC tests (F0, F1, F2)	Official Values	Official Values	Official & JRC test values	Speed profile & slope JRC tests
SiCO Mode	Not relevant	Official Values	Official Values	Official & JRC test values	Wheel Torque, Engine RPM JRC tests

3 Results and discussion

3.1 Chassis dynamometer measurements

The scope of the laboratory tests was twofold, to check the repeatability of the methodologies in the lab, under highly controlled conditions, with particular view on the transient testing cycles (i.e. Regional Delivery) and to investigate the quality of the simulations under different operating conditions. According to feedback received from involved stakeholders and indications from previous experimental campaigns the steady state tests (SiCO test) were expected to be highly repeatable in the laboratory. However, at the moment there were few data to support the repeatability of transient cycles. On the contrary feedback from stakeholders involved in testing suggested that on road fuel consumption testing exhibits poor repeatability. Further to the test's robustness the data would be used to compare the uncertainty of the simulation runs under transient conditions, and obtain a broader picture of VECTO's accuracy. These aspects were partially covered in the previous JRC study (Fontaras et al. 2016).

3.1.1 Vehicle #1

3.1.1.1 Steady State Tests

Table 4 describes the steady state points tested with vehicle #1 on the dyno. In this case torque measurements were conducted with a torque measurement device on the cardan shaft (Figure 10). All tests were preceded by at least 1h of vehicle warm up in order to achieve a minimum of 60°C for the axle and 75°C for the transmission lubricant and stabilize thermally the vehicle. Table 4 provides information regarding the vehicle's speed, the actual power measured at the cardan shaft, the gear engaged as well as the engine's and shaft's speed for each one of the 15 tested points. A repetition of each point is defined as a minimum of 60 s after stabilization phase. Measured shaft power and engine speed for each point shall not deviate more than ±10 kW and ±25 rpm between different measurements, otherwise the measurement is considered invalid.

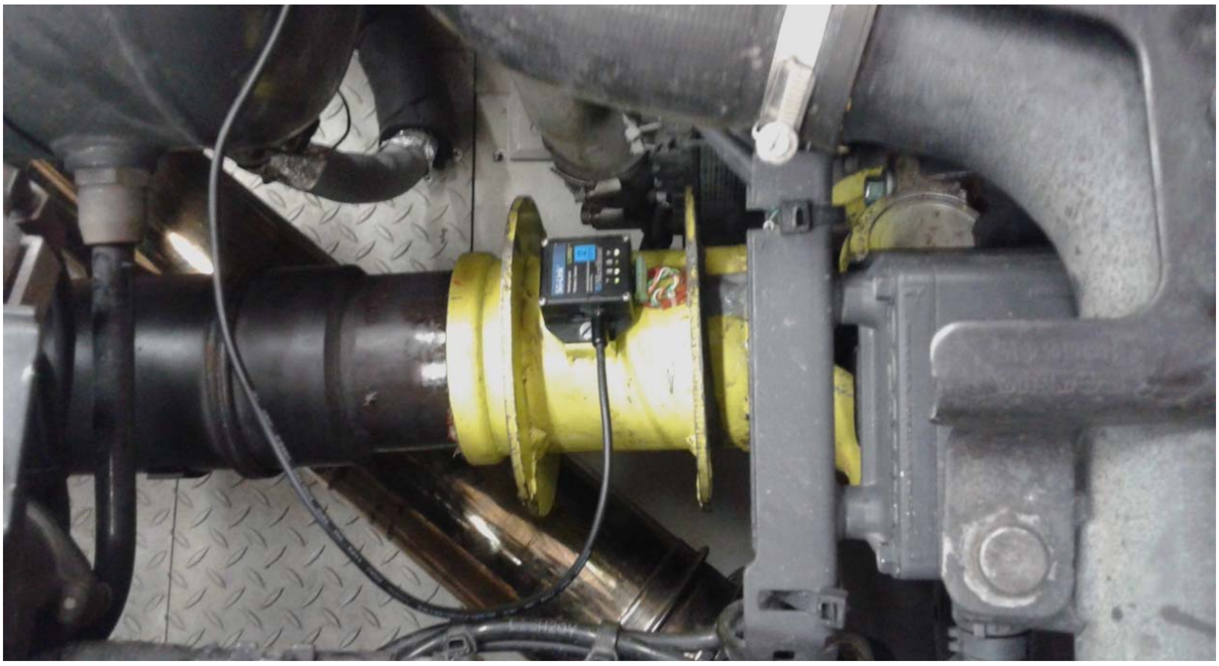

Figure 10: Torque measurement device on the cardan shaft of vehicle #1

Table 4: SiCO points for vehicle #1

#	Vehicle's Speed [km/h]	Power at Shaft [kW]	Engine Speed [RPM]	Shaft Speed [RPM]	Gear [-]
1	86.1	110.0	1252	1252	12
2	87.0	299.1	1249	1248	12
3	83.3	192.5	1220	1220	12
4	85.1	291.6	1222	1222	12
5	80.0	280.0	1179	1178	12
6	80.1	258.3	1178	1178	12
7	83.6	306.8	1481	1198	11
8	78.0	277.2	1150	1149	12
9	74.0	312.3	1311	1061	11
10	74.2	209.6	1315	1064	11
11	69.0	289.4	1223	990	11
12	69.8	141.8	1237	1001	11
13	67.6	103.3	1199	970	11
14	55.2	192.3	1230	792	10
15	55.2	96.3	1230	792	10

Table 5 briefly describes SiCO test results including the application of specific filters. In all cases measurements were conducted with A/C being switched off, while data with air compressor status "ON" were disregarded. All values given in Table 5 are averaged over 3 measurements, while ± values correspond to the standard deviation of the 3 measurements. Specific fuel consumption is normalized to the average value in g Fuel/kWh of all 15 SiCO points. The last column shows the relative standard deviation [%] of the three measurements of the fuel consumption (g Fuel/kWh) at the shaft (coefficient of variation).

Despite that high load points (i.e. shaft power >200 kW) come with high values of fuel consumption per hour (i.e. g Fuel/h), relatively low specific fuel consumption is observed. This is seen in points 2, 4, 5, 6, 7, 8 and 11 which all demonstrate specific fuel consumption lower than the average value of the 15 points (i.e. <1.0). On the other hand, medium load points (i.e. shaft power of 100-200 kW) showed specific fuel consumption higher than the average value of the 15 points (see points 1, 12, 13, 15). It could be concluded that lower load points are linked to higher specific fuel consumption. Unfortunately, this could not be confirmed for low load points (i.e. <50 kW) as they were not evaluated with vehicle #1 due to stability issues. More specifically it seems to be difficult for the dyno (and/or the analyzers) to perform repeatable runs of low load points with high accuracy, maybe due to the fact that relatively low forces are applied and therefore the relative error is maximized.

Coming to the repeatability of the SiCO test in the laboratory, it is seen from Table 5 that almost all points exhibited very low coefficient of variation (<1.5%). Only in the case of point 13 the relative standard deviation of the three measurements was higher than 2%. Of course, as mentioned previously this does not include low load points (i.e. <50 kW) which proved to be quite unstable and the measurements could not be repeated accurately.

Table 5: SiCO dyno test results for vehicle #1

Point [#]	Engine Speed [rpm]	Shaft Power [kW]	Normalized Specific FC at Shaft [g/kWh]	Relative SD [%]
1	1251±2	109.5±0.4	**1.096**	**1.1**
2	1250±1	299.2±0.8	**0.968**	**1.1**
3	1221±1	194.5±1.7	**0.989**	**1.3**
4	1221±1	291.9±0.7	**0.975**	**0.1**
5	1180±4	281.8±1.7	**0.972**	**1.0**
6	1181±5	259.8±1.8	**0.967**	**0.7**
7	1478±5	307.0±0.3	**0.989**	**0.4**
8	1152±5	276.4±0.8	**0.973**	**0.6**
9	1316±6	312.8±0.8	**0.980**	**0.2**
10	1316±5	210.1±0.8	**0.990**	**0.9**
11	1229±7	291.3±2.0	**0.974**	**0.6**
12	1229±7	141.5±0.3	**1.014**	**0.8**
13	1194±5	101.6±2.3	**1.061**	**2.5**
14	1228±2	191.9±0.6	**0.990**	**0.0**
15	1228±2	95.8±0.4	**1.061**	**0.2**

Table 6 briefly presents the comparison between measured and simulated fuel consumption values over the 15 SiCO points. Comparison is performed over normalized to the average of all measurements g Fuel/h value in order to better reflect the different FC over the whole range of points tested. Only VECTO SiCO mode was considered in this case. VECTO simulations were performed for one of the three available sequences of points. This practically means that Table 7 shows the direct comparison of the measured fuel consumption over this particular series and the respective simulated values and that no average values were considered for this comparison. The last column presents the deviation between the measured and the simulated fuel consumption values (g Fuel/kWh) for each point. The deviation between measured and simulated values is better depicted in Figure 11.

Table 6 shows that there is a good agreement between measured and simulated values for almost all examined points. High load points (i.e. shaft power >200 kW) showed deviations between measured and simulated values lower than 2%. Some medium load points (i.e. shaft power of 100-200 kW) showed slightly high deviations close to 3% (see points 13, 15). Again it seems that lower load points are linked to higher uncertainties compared to high load points. This could not be confirmed for low load points (i.e. <50 kW) as they were not evaluated with vehicle #1 due to stability issues.

Overall, it is concluded that there are no big difficulties in repeating steady state points in the lab. There is a question regarding low load points as they seem to be more difficult to be stabilized. Also, it seems from vehicle #1 that VECTO can simulate most points with a deviation from the measured value lower than 2%. Slightly higher deviations are found over lower load points. This shall not be neglected as important part of the fuel consumption occurs over low load points (Grigoratos et al. 2016).

Table 6: Measured vs. simulated fuel consumption over SiCO dyno test for vehicle #1

Point [#]	Engine Speed [rpm]	Shaft Power [kW]	Normalized FC VECTO [g Fuel/h]	Normalized FC Measured [g Fuel/h]	Deviation [%]
1	1252	110.0	0.634	0.644	**-1.5**
2	1249	299.1	1.531	1.556	**-1.6**
3	1220	192.5	1.013	1.034	**-2.1**
4	1222	291.6	1.501	1.525	**-1.6**
5	1179	280.0	1.447	1.476	**-1.9**
6	1178	258.3	1.330	1.349	**-1.4**
7	1481	306.8	1.629	1.622	**0.5**
8	1150	277.2	1.423	1.453	**-2.0**
9	1311	312.3	1.633	1.641	**-0.5**
10	1315	209.6	1.114	1.104	**0.9**
11	1223	289.4	1.516	1.522	**-0.4**
12	1237	141.8	0.782	0.777	**0.7**
13	1199	103.3	0.594	0.579	**2.7**
14	1230	192.3	1.024	1.019	**0.5**
15	1230	96.3	0.566	0.548	**3.3**

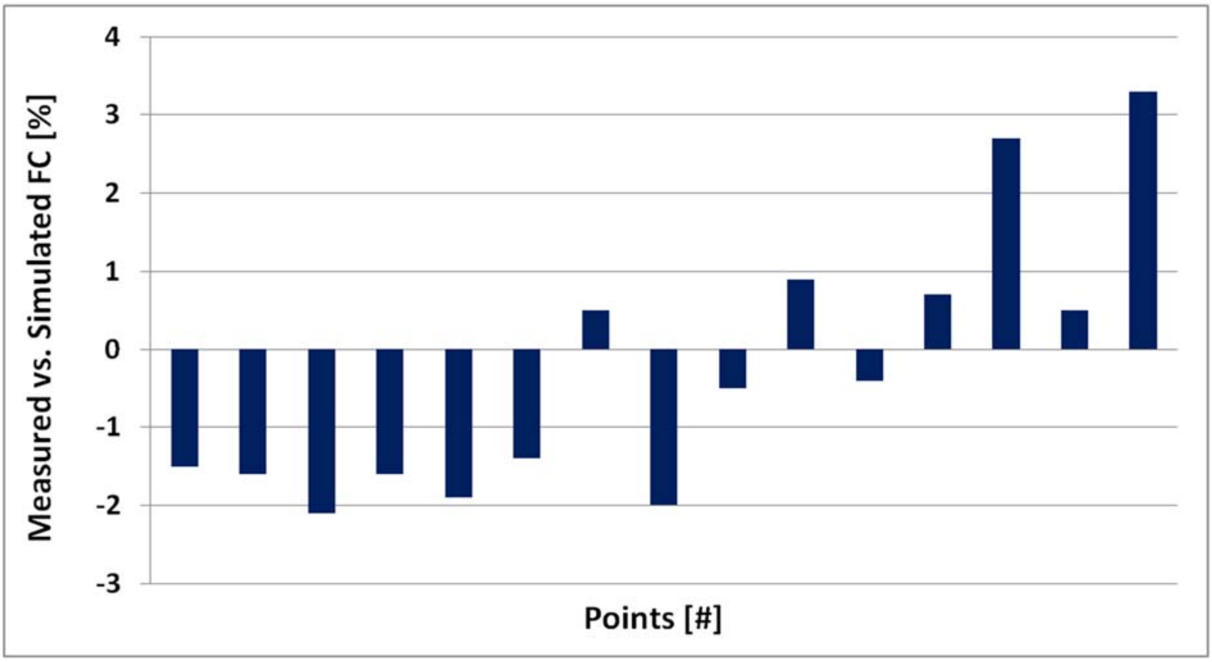

Figure 11: Deviation of the measured vs. the simulated FC values for all examined SS points

3.1.1.2 Transient Tests

Table 7 briefly describes WHVC and RD test results without the application of any filter. In all cases measurements were conducted with A/C being switched off. All transient tests were performed with at least 1h warming up of the vehicle, therefore all WHVCs are hot-start. Pull down of 20 kN was applied in order to avoid slipping of tyres. All values given in Table 8 are averaged over 3 measurements, while ± values correspond to the standard deviation of the 3 measurements. Specific fuel consumption has been normalized to the average value of all tested SiCO points in g Fuel/kWh. The last column represents the relative standard deviation [%] of the three measurements of fuel consumption (g Fuel/kWh) at the shaft (coefficient of variation).

Table 7: WHVC and Regional Delivery dyno test results for vehicle #1

Test	Average Speed [km/h]	Shaft Energy Measured [kWh]	Normalized Specific FC at Shaft [g/kWh]	Relative SD [%]
Regional Delivery	69.2±0.7	28.9±0.4	**1.095**	**1.3**
Hot Start WHVC	40.8±0.1	22.1±0.9	**1.437**	**3.7**

Table 7 shows that Regional Delivery cycle is highly repeatable in the laboratory. On the other hand, WHVC exhibited a coefficient of variation for the 3 different tests of about 4%. It has to be noted that there were several difficulties for the driver to reproduce braking events over transient cycles and mainly WHVC. Compared to RD, WHVC speed profile includes many more braking events and is characterized from generally lower speeds (average speed of 40.8 km/h vs. 69.2 km/h). This could explain the lower repeatability of WHVC compared to RD. Finally, normalized specific fuel consumption is found to be higher over the WHVC than the Regional Delivery due to the more transient nature of WHVC.

Table 8: Measured vs. simulated FC over WHVC and Regional Delivery for vehicle #1

Test	Average Speed [km/h]	Shaft Energy Measured [kWh]	Normalized FC VECTO [g/h]	Normalized FC Measured [g/h]	Deviation [%]
Regional Delivery	69.8	28.6	0.464	0.443	**4.7**
Hot Start WHVC	40.9	22.0	0.311	0.331	**-6.0**

Table 8 briefly presents the comparison between measured and simulated fuel consumption values over both transient cycles. Comparison is performed over normalized to the average of all measurements g Fuel/h value. Only VECTO in SiCO mode was tested for both transient cycles. Also in this case, VECTO simulations were performed for one of the 3 available tests for each cycle. This practically means that Table 8 shows the direct comparison of the measured fuel consumption over one WHVC and one RD with the simulated values of exactly the same run of WHVC and RD. Also, since VECTO SiCO mode uses as input the measured torque at the shaft, in this case the deviation between measured and simulated fuel consumption could be expressed both in g Fuel/h and g Fuel/kWh without being different. The deviation between measured and simulated values is also given in Figure 12.

As shown in Table 8 the total fuel consumption simulated with VECTO did not match very closely the experimentally measured for WHVC and RD cycles. The differences between calculated and measured results were up to 6%. Over the regional delivery the difference between measured and simulated fuel consumption was found to be at a 5% margin. The increased fuel consumption over the simulation suggests a possible overestimation of a particular vehicle load, possibly the consumption of some of the auxiliary systems. Furthermore, there is an offset due to torque drift which has not been corrected and overestimates the measured torque at the shaft. Similar deviation for the RD was reported previously for another truck tested by Fontaras et al. (2016). In any case we see that the accuracy of the simulations is lower compared to that of the steady state tests.

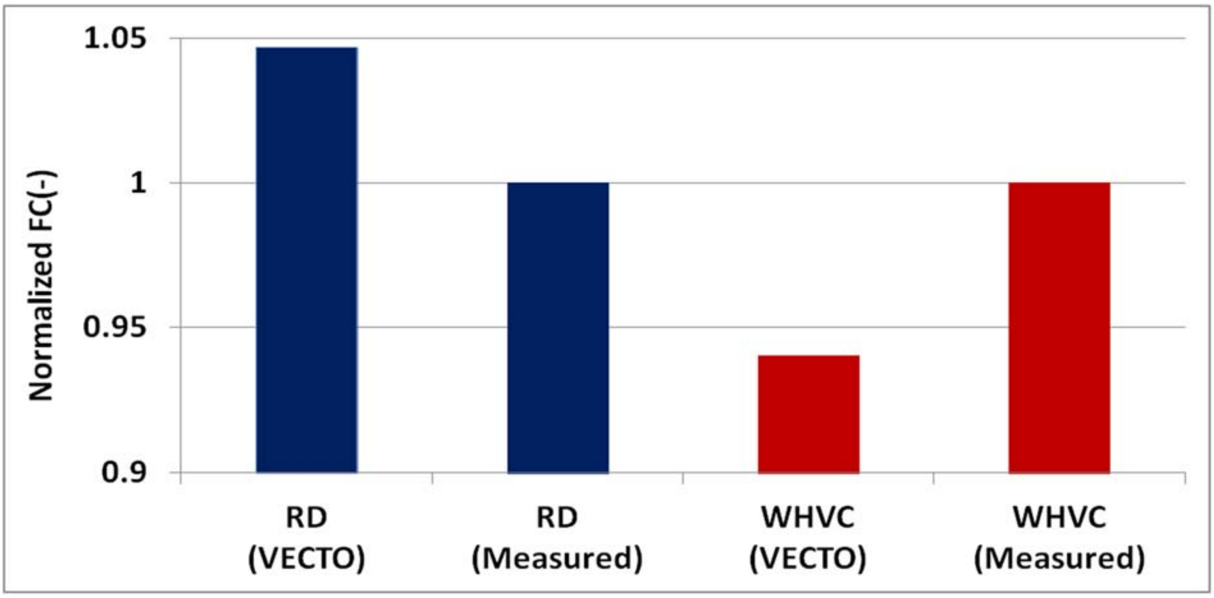

Figure 12: Normalized simulated vs. measured (=1.0) FC of vehicle #1 for WHVC and RD

Overall, it is concluded that while regional delivery is highly repeatable in the lab, this is not the case for WHVC. Increased number of braking events and generally lower speeds over WHVC seem to affect the repeatability of this cycle in the dyno. VECTO SiCO mode is able to simulate both cycles with, however, a relatively high deviation (approximately 5%) from the measured value. Slightly higher deviation is observed over WHVC.

3.1.2 Vehicle #2

3.1.2.1 Steady State Tests

Table 9 briefly presents the points tested with vehicle #2 in the dyno for the purposes of the SiCO test. Information regarding the vehicle’s speed, the actual power measured at the wheel, the gear engaged as well as the engine's speed for each one of the 17 tested points is given. Torque measurements were conducted with the Kistler torquemeter device placed at the wheel rims (Figure 13). All tests were performed with at least 1h warming up of the vehicle. A repetition of each point is defined as a minimum of 60 s after stabilization phase. Measured wheel power and engine speed for each point shall not deviate more than ±10 kW and ±25 rpm between different measurements.

Table 9: SiCO points for vehicle #2

#	Vehicle's Speed [km/h]	Power at Wheel [kW]	Engine Speed [RPM]	Shaft Speed [RPM]	Gear [-]
1	86.4	163.8	1178	1177	12
2	86.5	127.9	1178	1178	12
3	86.8	75.3	1178	1177	12
4	86.9	39.9	1178	1177	12
5	83.9	281.5	1472	1151	11
6	82.1	254.8	1124	1124	12
7	84.7	143.0	1475	1153	11
8	82.2	228.6	1124	1124	12
9	82.8	90.1	1124	1124	12
10	75.4	124.0	1026	1026	12
11	75.6	80.4	1026	1026	12
12	75.8	32.2	1026	1026	12
13	67.0	226.1	1176	919	11
14	58.8	152.8	1028	804	11
15	47.3	48.9	1318	642	9
16	43.3	169.9	1222	596	9
17	75.6	260.7	1327	1037	11

Table 10 presents SiCO test results filtered with regard to data with air compressor status "ON". Measurements were conducted with A/C being switched off. Values in Table 10 are averaged over 3 measurements and ± values correspond to the standard deviation of the 3 measurements. Vehicle specific fuel consumption is normalized to the average measured value (in g Fuel/kWh) of all examined SiCO points. The last column represents the relative standard deviation of the three measurements (g Fuel/kWh) elsewhere referred as coefficient of variation.

Like in case of vehicle #1, high load points (i.e. wheel power >200 kW) demonstrate the higher fuel consumption per hour but at the same time their vehicle specific fuel consumption is relatively low. Points 5, 6, 8, 13 and 17 all demonstrate VSFC lower than the average value of the 17 points (i.e. <1.0). On the other hand, medium to low load points (i.e. wheel power <100 kW) exhibited fuel consumption per kWh higher or very close to the average value of the 17 points (see points 3, 4, 9, 11, 12, 15) with low load points (i.e. wheel power <50 kW) being the most energy consuming (see points 4, 12, 15). Once more it is demonstrated that load points are linked to higher vehicle specific fuel consumption.

Figure 13: Torque measurement device at the wheels of vehicle #2

Table 10: SiCO dyno test results for vehicle #2

Point [#]	Engine Speed [rpm]	Wheel Power [kW]	Normalized VSFC [g/kWh]	Relative SD [%]
1	1178±0	163.8±1.2	**0.933**	**1.2**
2	1178±0	127.9±1.0	**0.952**	**0.4**
3	1178±0	75.3±0.9	**1.025**	**2.0**
4	1178±0	39.9±0.2	**1.248**	**1.9**
5	1472±0	281.5±0.2	**0.935**	**0.1**
6	1124±0	254.8±0.7	**0.911**	**0.1**
7	1475±5	143.0±0.9	**1.007**	**0.2**
8	1124±0	228.6±1.2	**0.914**	**0.7**
9	1124±0	90.1±1.3	**0.971**	**0.3**
10	1026±4	124.0±1.0	**0.935**	**0.5**
11	1026±4	80.4±1.6	**0.980**	**0.9**
12	1026±4	32.2±1.9	**1.274**	**4.4**
13	1176±5	226.1±1.5	**0.921**	**0.7**
14	1028±0	152.8±2.3	**0.938**	**1.1**
15	1318±0	48.9±1.9	**1.190**	**2.5**
16	1222±0	169.9±2.0	**0.933**	**0.7**
17	1327±0	260.7±2.9	**0.935**	**1.1**

When the repeatability of the SiCO test in the laboratory is examined, it is seen that almost all steady state points exhibited low coefficient of variation (<2.0%). Most points proved to be highly repeatable (coefficient of variation <1%) and only in the case of points 12 and 15 the relative standard deviation of the 3 measurements was higher than 2%. Unstable points are low load points, therefore in conjunction with the observations from vehicle #1 it can be concluded that low load points are quite unstable and not easy to be repeated accurately.

Table 11 briefly presents the comparison between measured and simulated fuel consumption over the 17 steady state points. Comparison is performed over normalized to the average of all measurements g Fuel/h value in order to better reflect the different FC over the whole range of points tested. The simulations were run with VECTO SiCO mode (3.0.3.495 version) for one of the three available sequences of points. The last column presents the deviation between the measured and the simulated fuel consumption values (g Fuel/h) for each point. The deviation between measured and simulated values is also graphically given in Figure 14.

Table 11: Measured vs. simulated fuel consumption over SiCO dyno test for vehicle #2

Point [#]	Engine Speed [rpm]	Wheel Power [kW]	Normalized FC VECTO [g Fuel/h]	Normalized FC Measured [g Fuel/h]	Deviation [%]
1	1178	165.1	1.215	1.218	**-0.2**
2	1178	129.0	0.973	0.973	**0.0**
3	1178	76.4	0.628	0.609	**3.1**
4	1178	40.2	0.402	0.392	**2.5**
5	1472	281.7	2.070	2.095	**-1.2**
6	1124	254.1	1.120	1.843	**-0.7**
7	1472	142.4	1.830	1.140	**-1.8**
8	1124	227.2	1.650	1.665	**-0.9**
9	1124	88.7	0.718	0.685	**4.8**
10	1031	123.0	0.940	0.920	**2.1**
11	1031	78.7	0.646	0.618	**4.5**
12	1031	30.2	0.330	0.321	**2.9**
13	1181	224.6	1.652	1.659	**-0.4**
14	1028	150.3	1.148	1.135	**1.1**
15	1318	46.9	0.472	0.456	**3.6**
16	1222	167.6	1.266	1.254	**1.0**
17	1327	257.3	1.900	1.938	**-2.0**

Table 11 demonstrates that there is a good agreement between measured and simulated values for all high load points (i.e. wheel power >200 kW). Deviations between measured and simulated values did not exceed 2%. Also medium to high load points (i.e. wheel power of 100-200 kW) exhibited very good repeatability close to 1% (see points 1, 8, 14, 16). Medium to low load points (i.e. wheel power of 50-100 kW) and low load points (i.e. wheel power <50 kW) are linked to higher uncertainties compared to high load points. The most difficult points to reproduce and therefore with the highest values of deviation

(>3%) proved to be these of approximately 80 kW wheel power (see points 3, 9, 11). Similar conclusions were drawn for vehicle #1.

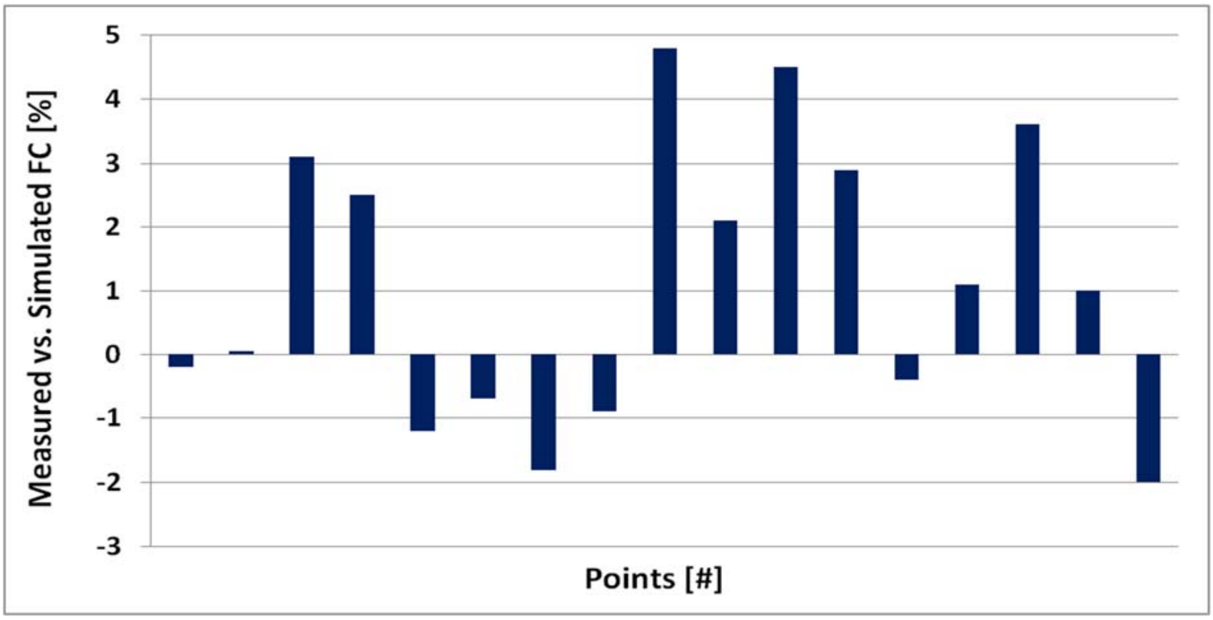

Figure 14: Deviation of the measured vs. the simulated FC values for all examined SS points

Overall, it is concluded that steady state points are satisfactorily repeatable in the lab with a bigger deviation when it comes to low load points. Even in the very advanced chassis dyno of VELA 7 low load points seem to be more difficult to be stabilized. VECTO can simulate medium to high and high load points with a deviation from the measured value lower than 2%. Slightly higher deviations are found over medium to low and low load points making the method questionable at least at this range of loads. This is an important issue related to the SiCO method as important part of fuel consumption occurs over low load points.

3.1.2.2 Transient Tests

Table 12 shows WHVC and Regional Delivery test results without the application of any filter. Measurements were conducted with A/C being switched off. All transient tests were performed with at least 1h warming up of the vehicle with an application of 20 kN pull down to avoid slipping of tyres. Values given in Table 12 are averaged over 3 measurements performed over different days. Vehicle specific fuel consumption is normalized to the average value in g Fuel/kWh of all SiCO points tested. The last column represents the coefficient of variation of 3 measurements of the VSFC (g Fuel/kWh).

Table 12 shows that both transient cycles tested are quite repeatable in the laboratory. In this case and despite the difficulty of the driver to reproduce some braking events over WHVC, this cycle proved to be highly repeatable. WHVC was selected to perform a cross check of the AMA performance. For that reason the AVL KMA fuel flowmeter was connected and the values of the two instruments were compared. WHVC was selected because it is a highly transient cycle and therefore representative of many different operating conditions and engine loads. The difference among the two instruments was found to range from 0.5-1.0% depending on the test. This range of deviation is considered low taking into account the analyser inaccuracies. Once more, normalized fuel consumption is higher over the WHVC than the Regional Delivery due to the more transient nature of WHVC.

Table 12: WHVC and Regional Delivery dyno test results for vehicle #2

Test	Average Speed [km/h]	Wheel Energy Measured [kWh]	Normalized VSFC [g/kWh]	Relative SD [%]
Regional Delivery	67.8±0.3	31.6±0.3	**0.979**	**1.4**
Hot Start WHVC	39.2±1.2	25.3±0.2	**1.018**	**0.1**

Table 13 presents the comparison between measured and simulated fuel consumption values over Regional Delivery. Comparison is performed over normalized to the average of all measurements g Fuel/h value. VECTO SiCO mode in 2 different versions (with 4.51 kW additional auxiliaries consumption and without any P_{add}) was considered in this case. Unfortunately, no comparison is available for the WHVC cycle. VECTO simulations for Regional Delivery were performed for two out of the three available tests and all results are given in Table 13. Since VECTO SiCO mode uses as input the measured torque at the wheel also in this case the deviation between measured and simulated fuel consumption could be expressed both in g Fuel/h and g Fuel/kWh without any difference. The deviation between measured and simulated values is also depicted in Figure 15.

Table 13: Measured vs. simulated FC over Regional Delivery tests for vehicle #2

Test	Average Speed [km/h]	Wheel Energy Measured [kWh]	Normalized FC VECTO w/o P_{add} [g/h]	Normalized FC VECTO with P_{add} [g/h]	Normalized FC Measured [g/h]	Deviation Measured vs. No P_{add} [%]	Deviation Measured vs. 4.51kW P_{add} [%]
Regional Delivery 1	68.1	31.2	0.641	0.668	0.650	**-1.5**	**2.7**
Regional Delivery 2	68.0	31.7	0.647	0.674	0.647	**0.0**	**4.2**
Regional Delivery Averaged	68.1	31.5	0.644	0.671	0.649	**-0.8**	**3.4**

As shown in Table 13 the total fuel consumption calculated by VECTO was very close to the measured value when no P_{add} was applied. Actually, the deviation between measured and simulated FC was at the same level as stable state points. On the other hand, the total fuel consumption simulated by VECTO was found to be less precise with the 4.51kW P_{add} version. The difference with the latest reached 4% and was similar to that found with the vehicle #1 over the same cycle. Increased fuel consumption over the simulation suggests a possible overestimation of the consumption of some of the auxiliary systems. In any case we see that the accuracy of the simulations with vehicle #2 is similar to that of the steady state tests.

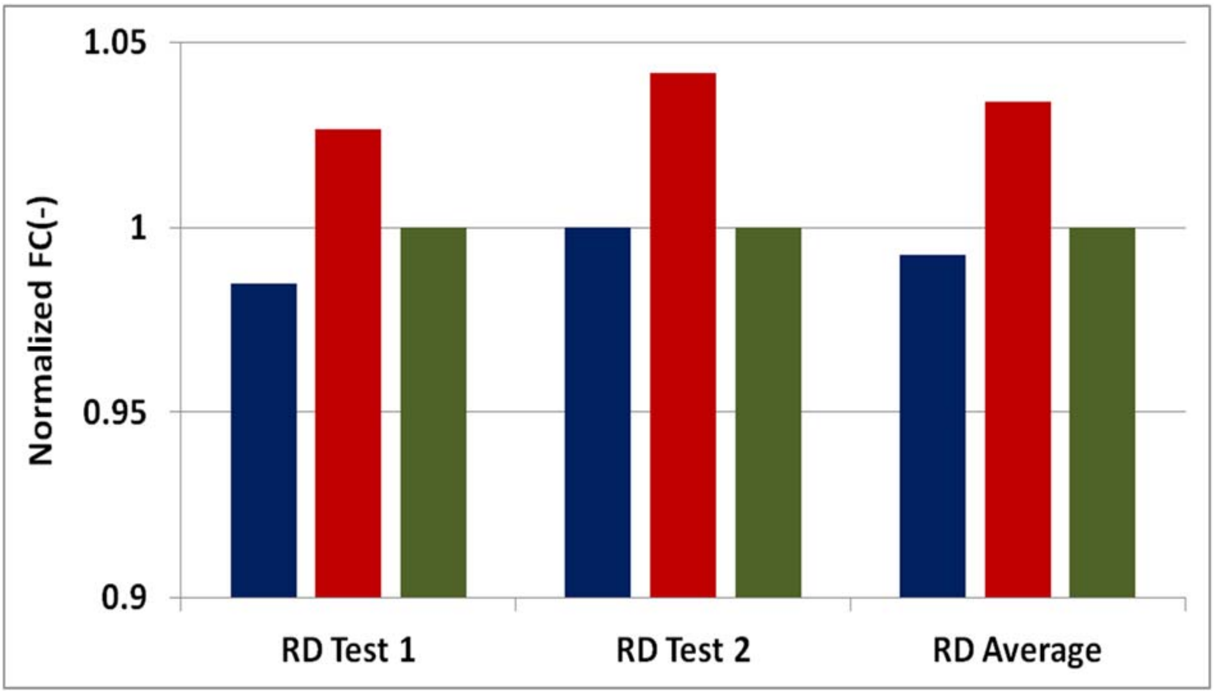

Figure 15: Normalized simulated (w/o P_{add} blue bars – 4.51kW P_{add} red bars) vs. measured (=1.0 – green bars) FC of vehicle #2 for Regional Delivery tests

Overall, it is concluded that both transient cycles are highly repeatable in the laboratory in contrast to what was seen with vehicle #1. VECTO SiCO mode seems to be able to simulate Regional Delivery cycle quite accurately with both modes and slightly better when no P_{add} is applied. No test demonstrated deviation higher than 5%.

3.1.3 Vehicle #3

3.1.3.1 Steady State Tests

Table 14 describes the 16 steady state points tested with vehicle #3 in the dyno for the SiCO test. Information regarding the vehicle's speed, the actual power measured at the wheel, the gear engaged as well as the engine's speed for each point is given. Also in this case torque measurements were conducted with the Kistler torquemeter device placed at the wheel rims. Shaft speed was not recorded in this case as the respective signal from the CAN was missing. All tests were performed with at least 1h warming up of the vehicle. A repetition of each point is defined as a minimum of 60 s after stabilization phase. Wheel power and engine speed for each one of the 16 points shall not deviate more than ±10 kW and ±25 rpm between different measurements otherwise the measurement is considered invalid.

Table 15 shows SiCO test results of vehicle #3. In all cases measurements were conducted with A/C being switched off, while data with air compressor status "ON" were disregarded. Values are averaged over 3 measurements and ± values correspond to the SD of the 3 measurements. Vehicle specific fuel consumption is normalized to the average value of all measured SiCO points in g Fuel/kWh. The last column represents the relative standard deviation of the three measurements (g Fuel/kWh).

Despite the fact that vehicle #3 is different from the other vehicles with respect to its maximum load and engine characteristics, there were no significant differences in its behavior on the chassis dyno at least with regard to the SiCO test. High load points (i.e. wheel power >150 kW – different for this truck compared to the other three) demonstrated the higher fuel consumption in g Fuel/h, while at the same time normalized vehicle specific fuel consumption is relatively low. For instance points 1, 5, 7, 10, 12, 13 and 14 all exhibited fuel consumption per kWh lower than the average value of the 16 points (i.e. <1.0). On the other hand, low load points (i.e. wheel power close to or <50 kW) exhibited normalized fuel consumption higher or very close to the average value of the 16 points (see points 6, 11, 15).

Table 14: SiCO points for vehicle #3

#	Vehicle's Speed [km/h]	Power at Wheel [kW]	Engine Speed [RPM]	Shaft Speed [RPM]	Gear [-]
1	84.7	161.1	1420	*	9
2	83.8	138.7	1403	*	9
3	84.0	103.1	1403	*	9
4	84.2	76.0	1403	*	9
5	81.8	157.1	1370	*	9
6	82.5	30.3	1371	*	9
7	77.9	150.0	1306	*	9
8	74.0	156.5	1648	*	8
9	64.5	75.0	1431	*	8
10	63.1	151.2	1409	*	8
11	63.7	55.1	1409	*	8
12	60.2	149.3	1344	*	8
13	54.1	173.0	1633	*	7
14	49.6	167.5	1497	*	7
15	48.0	36.8	1429	*	7
16	46.6	118.4	1400	*	7

From Table 15 it is seen that most steady state points proved to be highly repeatable as almost all points exhibited low coefficient of variation (<2.0%). Only in the case of points 11 and 15 the relative standard deviation of the 3 measurements was higher than 2%. Once more, higher instability is observed for low load points.

Table 16 presents the comparison between measured and simulated fuel consumption over the 16 steady state points. Comparison is performed over normalized to the average of all measurements g Fuel/h value in order to better reflect the different FC over the whole range of points tested. The simulations were run with VECTO SiCO mode (3.0.2.466 version) for one of the three available sequences of points. The last column presents the deviation [%] between the measured and the simulated fuel consumption values (g Fuel/kWh) for each point. The deviation between measured and simulated values is also graphically given in Figure 16.

Table 15: SiCO dyno test results for vehicle #3

Point [#]	Engine Speed [rpm]	Wheel Power [kW]	Normalized VSFC [g/kWh]	Relative SD [%]
1	1420±0.1	161.1±1.2	**0.956**	**1.5**
2	1403±0.0	138.7±0.7	**0.964**	**2.1**
3	1403±0.0	103.1±0.4	**0.978**	**1.9**
4	1403±0.1	76.0±0.2	**1.018**	**0.4**
5	1370±0.5	157.1±0.5	**0.947**	**0.7**
6	1371±0.2	30.3±0.6	**1.272**	**0.2**
7	1306±0.1	150.0±1.1	**0.937**	**1.3**
8	1648±0.1	156.5±1.4	**0.947**	**0.3**
9	1431±0.0	75.0±1.3	**0.995**	**0.1**
10	1409±0.2	151.2±1.2	**0.921**	**0.7**
11	1409±0.1	55.1±1.8	**1.035**	**3.2**
12	1344±0.3	149.3±1.5	**0.922**	**1.4**
13	1633±0.1	173.0±2.2	**0.975**	**0.7**
14	1497±16.7	167.5±1.6	**0.962**	**1.2**
15	1429±0.1	36.8±1.7	**1.218**	**3.3**
16	1400±0.1	118.4±1.6	**0.953**	**1.7**

Table 16 shows a lack of agreement between measured and simulated values regardless the examined load. Deviations up to 8% were observed both for high (i.e. wheel power >150 kW) and low (i.e. wheel power <50 kW) load points. Only some medium load points (i.e. wheel power of 80-120 kW) demonstrated a fair repeatability of 1.5-2.5% (see points 3, 4, 9, 16), which can be compared to this of the other examined vehicles. VECTO seems to underestimate most of the measured points. One source of the error is probably the false Air-Compressor status signal received by the CAN. It seems that there was a constant signal showing that the Air-Compressor was always switched off even if it was functioning. This way there were no data to disregard leading to an increased measured fuel consumption with respect to the one simulated by the tool.

Overall, it is once more confirmed that steady state points are satisfactorily repeatable in the lab with however a higher uncertainty when it comes to low load points. Difficulties trying to repeat low load steady state points have been also reported by the respective OEMs. In this case, VECTO failed to accurately simulate steady state points. This is partially attributed to a false signal of the Air Compressor status received by the ECU. Slightly lower deviations are found over medium load points.

Table 16: Measured vs. simulated fuel consumption over SiCO dyno test for vehicle #3

Point [#]	Engine Speed [rpm]	Wheel Power [kW]	Normalized FC VECTO [g Fuel/h]	Normalized FC Measured [g Fuel/h]	Deviation [%]
1	1420	159.8	1.477	1.584	**-6.7**
2	1403	138.1	1.279	1.385	**-7.7**
3	1403	102.8	1.022	1.037	**-1.4**
4	1403	75.9	0.774	0.795	**-2.6**
5	1371	157.0	1.448	1.515	**-4.4**
6	1371	30.7	0.374	0.396	**-5.7**
7	1306	151.2	1.389	1.435	**-3.2**
8	1648	156.9	1.516	1.523	**-0.5**
9	1431	76.5	0.799	0.778	**2.6**
10	1409	152.3	1.439	1.423	**1.2**
11	1409	57.2	0.617	0.583	**5.9**
12	1344	151.0	1.422	1.403	**1.3**
13	1633	175.5	1.644	1.752	**-6.2**
14	1487	168.4	1.563	1.665	**-6.3**
15	1429	38.7	0.439	0.466	**-5.8**
16	1400	120.2	1.127	1.144	**-1.6**

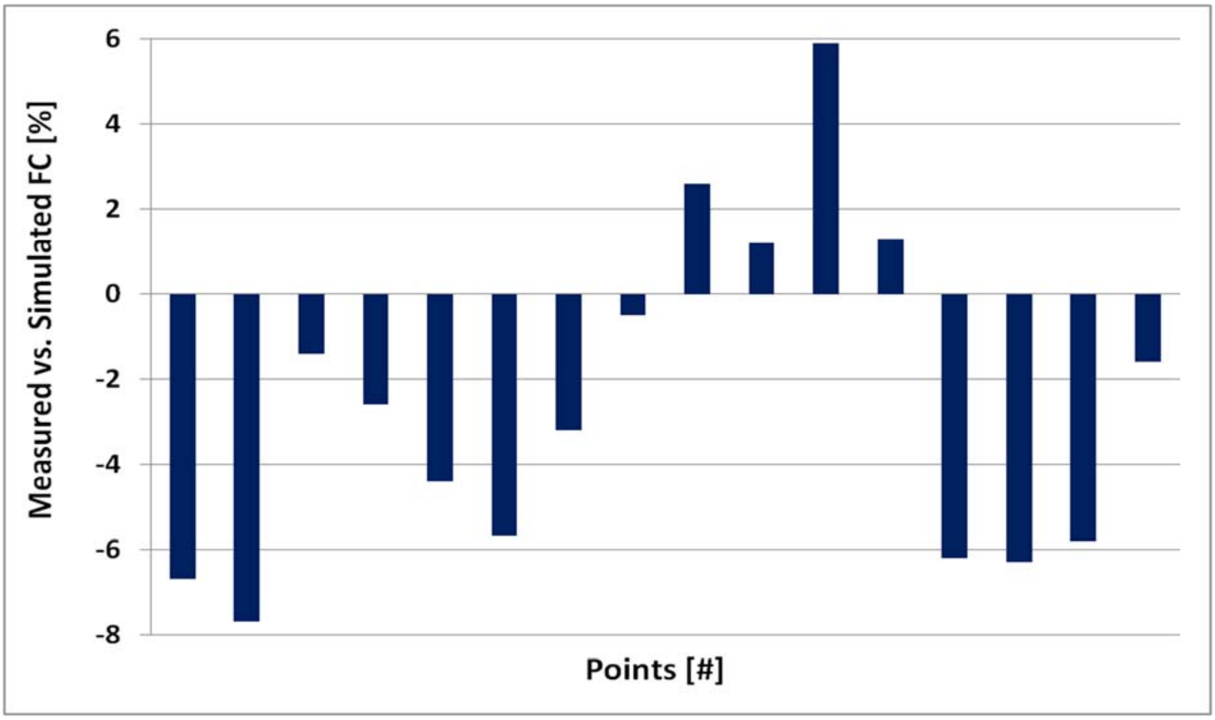

Figure 16: Deviation of the measured vs. the simulated FC values for all examined SS points

3.1.3.2 Transient Tests

Table 17 shows WHVC and Regional Delivery test results without the application of any filter. Measurements were conducted with A/C being switched off and after 1h warming up of the vehicle. Values are averaged over 3 measurements which were performed over different days. Vehicle specific fuel consumption is normalized to the average value of the 16 steady state points tested. The last column represents the coefficient of variation of 3 measurements of the fuel consumption at wheel (g Fuel/kWh).

Table 17**:** WHVC and Regional Delivery dyno test results for vehicle #3

Test	Average Speed [km/h]	Wheel Energy Measured [kWh]	Normalized VSFC [g/kWh]	Relative SD [%]
Regional Delivery	69.1±0.4	23.7±0.1	**1.038**	**0.9**
Hot Start WHVC	39.9±0.4	16.8±0.1	**1.184**	**2.7**

Table 17 shows that both transient cycles are satisfactorily repeatable in the laboratory. WHVC exhibited a coefficient of variation for the three different tests of about 3%. This observation is similar to vehicle #1 and can be attributed to the fact that WHVC cycle is too dynamic to stay within the speed band and in any case it is more transient than the RD. On the other hand, Regional Delivery proved to be highly repeatable with the coefficient of variation for the 3 different tests not exceeding 1% in accordance with the results of the other trucks. Finally, normalized fuel consumption is higher over the WHVC than the Regional Delivery due to the more transient nature of WHVC.

Table 18**:** Measured vs. simulated FC over Regional Delivery tests for vehicle #3

Test	Average Speed [km/h]	Normalized FC VECTO SiCO Mode [g/h]	Normalized FC VECTO Eng. Mode [g/h]	Normalized FC Measured [g/h]	Deviation Measured vs. SiCO [%]	Deviation Measured vs. Eng. [%]
Regional Delivery 1	69.1	0.668	0.832	0.676	**-1.1**	**-7.9**
Regional Delivery 2	68.7	0.658	0.825	0.668	**-1.4**	**-8.4**
Regional Delivery 3	69.4	0.663	0.837	0.675	**-1.7**	**-8.9**
Regional Delivery Averaged	69.1±0.4	0.663	0.831	0.673	**-1.4**	**-8.4**
WHVC	39.9	0.393	0.545	0.405	**-2.8**	**-13.6**

Table 18 shows the details of the comparison between measured and simulated fuel consumption values over all Regional Delivery tests as well as over the one WHVC test that was selected to be simulated. Comparison is performed over normalized to the average of all measurements g Fuel/h value. Both VECTO SiCO and Engineering modes were considered in this case for the simulations. The deviation between measured and simulated fuel consumption is calculated using the fuel consumption at the wheel in g Fuel/h. The deviation between measured and simulated values is graphically given in Figure 17.

As shown in Table 18 the total fuel consumption calculated by VECTO SiCO mode was very close to the measured value both for Regional Delivery and WHVC tests. Deviations lower than 2% were found for the RD cycle, while it was found to be somewhat higher for the WHVC (3%). On the other hand, the total fuel consumption simulated by VECTO Engineering mode was found to be very far from the measured value with deviations being as high as 9%. The difference was even higher for the unique WHVC test examined. In all cases the VECTO Engineering mode underestimates the fuel consumption suggesting a possible underestimation of the consumption of some of the auxiliary systems.

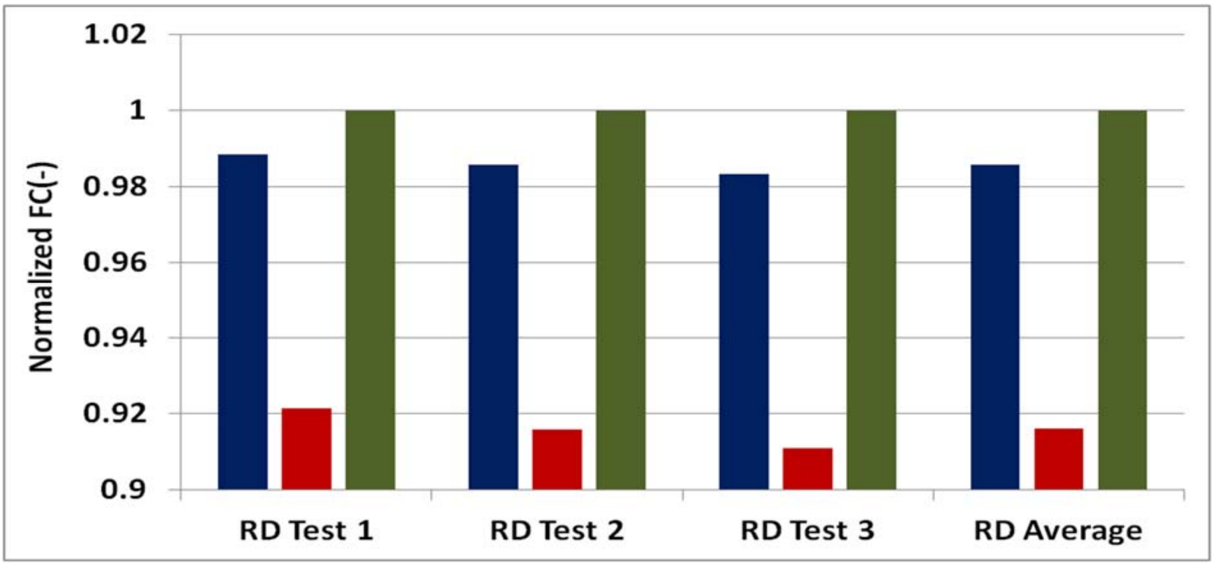

Figure 17: Normalized simulated (SiCO mode blue bars – Engineering Mode red bars) vs. measured (=1.0 – green bars) FC of vehicle #3 for Regional Delivery tests

Overall, it is once more demonstrated that both transient cycles are satisfactorily repeatable in the laboratory with Regional Delivery being much easier to replicate compared to WHVC. VECTO SiCO mode seems to be able to simulate both transient cycles quite accurately, whereas the VECTO Engineering mode failed to do so. There is no obvious reason for this big difference among the two modes and clearly there is a need for further investigation.

3.1.4 Vehicle #4

3.1.4.1 Steady State Tests

Table 19 describes the stable state points tested with vehicle #4 in the dyno. Also in this case measurements were conducted with A/C being switched off. Torque measurements were conducted with the Kistler torquemeter device placed at the wheel rims. All tests were performed with at least 1h warming up of the vehicle. A repetition of each point is defined as a minimum of 60 s after stabilization phase. Measured wheel power and engine speed for each point shall not deviate more than ±10 kW and ±25 rpm between different measurements otherwise the measurement is considered invalid.

Table 19: SiCO points for vehicle #4

#	Vehicle's Speed [km/h]	Wheel Power [kW]	Engine Speed [RPM]	Shaft Speed [RPM]	Gear [-]
1	83.4	265.8	1153	1153	12
2	84.0	130.5	1153	1152	12
3	84.5	24.3	1153	1152	12
4	81.8	200.5	1125	1125	12
5	82.0	158.0	1126	1125	12
6	82.1	121.7	1126	1125	12
7	82.3	72.4	1126	1125	12
8	80.6	234.1	1112	1111	12
9	76.5	244.7	1056	1055	12
10	73.5	266.2	1308	1016	11
11	64.5	252.1	1150	893	11
12	65.2	109.5	1150	893	11
13	65.4	65.6	1150	893	11
14	61.6	250.5	1099	854	11
15	70.4	291.0	1590	975	10
16	66.4	290.9	1501	921	10
17	50.9	175.2	1146	703	10
18	51.4	48.6	1146	703	10

Table 20 briefly describes SiCO test results including the application of specific filters (i.e. A/C switched off, data with air compressor status "ON" disregarded). All values are averaged over 3 measurements, while ± values correspond to the standard deviation of the 3 measurements. Fuel consumption was recorded from the PEMS instrument as there were some issues with the AMA device. Vehicle specific fuel consumption is normalized to the average value of all 18 points measured in g Fuel/kWh. The last column represents the coefficient of variation of the 3 fuel consumption measurements (g Fuel/kWh).

High load points (i.e. wheel power >200 kW) showed higher fuel consumption in g Fuel/h (Table 21) but relatively low fuel consumption per kWh. This is seen in points 1, 10, 11, 14, 15 and 16 which all showed fuel consumption per kWh lower than the average value of the 18 points (i.e. <1.0). Medium to low load points (i.e. wheel power of 100-200 kW) showed vehicle specific fuel consumption close to the average value of the 18 points (see points 2, 6, 12). On the other hand lower load points (i.e. wheel power <70 kW) demonstrated higher normalized fuel consumption than the average of the 18 points (see points 3, 13, 18). This observation is confirmed for all tested vehicles.

Table 20: SiCO dyno test results for vehicle #4

Point [#]	Engine Speed [rpm]	Wheel Power [kW]	Normalized VSFC [g/kWh]	Relative SD [%]
1	1153±2.6	265.8±2.0	**0.931**	**0.4**
2	1153±2.5	130.5±1.4	**0.971**	**0.2**
3	1153±2.5	24.3±0.9	**1.537**	**0.8**
4	1125±2.7	200.5±1.0	**0.926**	**1.0**
5	1126±2.2	158.0±0.9	**0.941**	**0.7**
6	1126±2.7	121.7±1.3	**0.963**	**1.3**
7	1126±2.6	72.4±0.8	**1.051**	**0.5**
8	1112±2.9	234.1±0.9	**0.924**	**1.0**
9	1056±2.6	244.7±1.2	**0.935**	**1.0**
10	1308±2.9	266.2±0.7	**0.928**	**0.8**
11	1150±2.4	252.1±0.9	**0.946**	**0.7**
12	1150±2.5	109.5±0.6	**0.981**	**0.3**
13	1150±2.3	65.6±0.5	**1.061**	**0.0**
14	1099±3.1	250.5±0.3	**0.951**	**1.0**
15	1590±3.3	291.0±0.7	**0.937**	**0.4**
16	1501±3.2	290.9±0.9	**0.936**	**0.5**
17	1146±4.1	175.2±0.9	**0.947**	**0.5**
18	1146±3.7	48.6±1.4	**1.133**	**1.3**

Regarding the repeatability of the SiCO test in the laboratory once more it is demonstrated that most points exhibit very low coefficient of variation (<1.5%). In this case no point exhibited relative standard deviation of the three measurements higher than 2%. Even low load points (i.e. <50 kW) proved to be quite stable with relative standard deviation of 0.8 and 1.3%.

Table 21 briefly presents the comparison between measured and simulated (VECTO SiCO mode - 3.0.3 version) fuel consumption values over the 18 SiCO points. Comparison is performed over normalized to the average of all measurements g Fuel/h value in order to better reflect the different FC over the whole range of points tested. VECTO simulations were performed for one of the three available sequences of points. This practically means that Table 21 presents the direct comparison of the measured fuel consumption over this particular series and the respective simulated values. The last column presents the deviation [%] between the measured and the simulated fuel consumption values (g Fuel/kWh) for each point. The deviation between measured and simulated values is also graphically presented in Figure 18.

Also in this case there is not a good agreement between measured and simulated values, regardless the point examined. All points demonstrated a deviation higher than 3%, while in some cases it exceeded 10%. In all cases VECTO SiCO mode underestimates the fuel consumption suggesting a possible underestimation of the load or/and the consumption of some of the auxiliary systems. This behavior is similar to that of vehicle #3.

Table 21: Measured vs. simulated fuel consumption over SiCO dyno test for vehicle #4

Point [#]	Engine Speed [rpm]	Wheel Power [kW]	Normalized FC VECTO [g Fuel/h]	Normalized FC Measured [g Fuel/h]	Deviation [%]
1	1155	264.1	1.532	1.668	**-4.8**
2	1154	129.3	0.765	0.829	**-7.0**
3	1155	23.9	0.209	0.244	**-12.8**
4	1128	200.2	1.156	1.266	**-4.2**
5	1127	157.5	0.918	0.976	**-5.4**
6	1128	121.4	0.719	0.766	**-5.4**
7	1128	72.0	0.453	0.488	**-8.3**
8	1114	234.0	1.358	1.462	**-3.5**
9	1054	243.6	1.432	1.539	**-3.3**
10	1310	265.6	1.499	1.679	**-6.8**
11	1150	251.1	1.422	1.608	**-8.4**
12	1150	108.9	0.643	0.701	**-8.0**
13	1150	65.2	0.410	0.453	**-9.7**
14	1102	250.8	1.368	1.593	**-11.7**
15	1592	290.6	1.656	1.859	**-6.7**
16	1503	290.5	1.647	1.853	**-7.2**
17	1142	174.4	0.997	1.091	**-7.5**
18	1143	48.3	0.321	0.356	**-11.1**

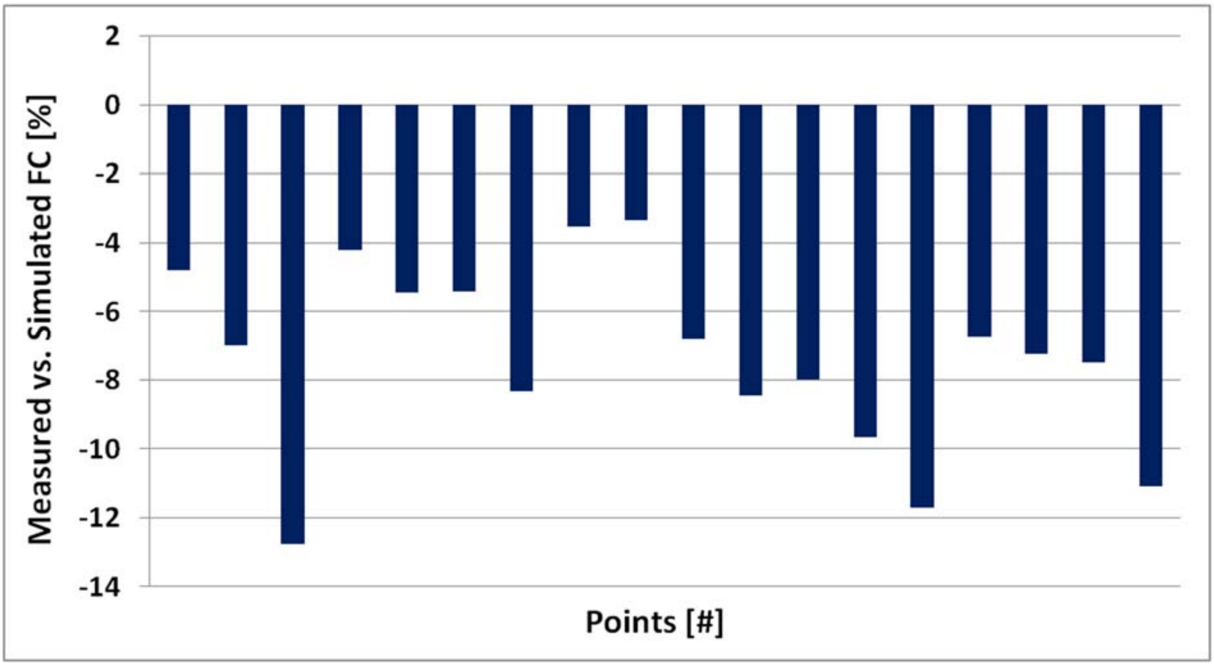

Figure 18: Deviation of the measured vs. the simulated FC values for all examined SS points

Overall, it is concluded that there are no big difficulties in repeating steady state points in the lab. There is a question regarding low load points as they seem to be more difficult to be stabilized. However, VECTO doesn't seem capable of simulating steady state points with a deviation from the measured value lower than 3%.

3.1.4.2 Transient Tests

Table 22 briefly describes WHVC and RD test results without the application of any filter. Measurements were conducted with at least 1h warming up of the vehicle and A/C being switched off. Pull down of 20 kN was applied in order to avoid slipping of tyres. All values are averaged over 3 measurements and ± correspond to the standard deviation of the measurements. Fuel consumption is given in normalized to the average of SiCO points value as g Fuel/kWh. The last column represents the coefficient of variation of the 3 different fuel consumption measurements (g Fuel/kWh).

Table 22: WHVC and Regional Delivery dyno test results for vehicle #4

Test	Average Speed [km/h]	Wheel Energy Measured [kWh]	Normalized VSFC [g/kWh]	Relative SD [%]
Regional Delivery	68.0±0.4	31.1±0.2	**1.001**	**0.6**
Hot Start WHVC	39.9±0.7	23.9±0.9	**1.132**	**3.1**

Once more it is demonstrated that Regional Delivery cycle is highly repeatable in the chassis dyno of the VELA 7. On the other hand, WHVC exhibited a coefficient of variation for the three different tests that were considered of about 3%. This deviation is similar to that of vehicles #1 and #3. Again there were several difficulties for the driver to reproduce braking events particularly over WHVC. Also it is seen that normalized fuel consumption is higher over the WHVC than the Regional Delivery due to the more transient nature of WHVC.

Table 23 briefly presents the measured vs. simulated fuel consumption values over the Regional Delivery cycle. Comparison is performed over normalized to the average of all measurements g Fuel/h value. Only VECTO SiCO mode was considered for the simulations. Unfortunately, no comparison is available for the WHVC cycle. VECTO simulations for Regional Delivery were performed for all three available tests. Also, since VECTO SiCO mode uses as input the measured torque at the wheel, in this case the deviation between measured and simulated fuel consumption could be expressed both in g Fuel/h and g Fuel/kWh. The deviation between measured and simulated values is also given in Figure 19.

As shown in Table 23 the total fuel consumption simulated with VECTO matched satisfactorily the experimentally measured for all Regional Delivery cycles. The difference between calculated and measured fuel consumption values did not exceed 4% for individual tests, while the averaged deviation was found to be lower than 3%. Again, the VECTO underestimates actual fuel consumption but in this case there is no significant difference like in case of steady state points. Similar deviation for the Regional Delivery was also found for the other trucks tested.

Table 23: Measured vs. simulated FC over Regional Delivery cycle for vehicle #4

Test	Average Speed [km/h]	Wheel Energy Measured [kWh]	Normalized FC VECTO [g/h]	Normalized FC Measured [g/h]	Deviation [%]
Regional Delivery #1	67.6	31.0	0.514	0.528	**-4.0**
Regional Delivery #2	68.0	31.0	0.513	0.533	**-3.9**
Regional Delivery #3	68.4	31.4	0.535	0.537	**-0.5**
Regional Delivery Average	**68.0±0.4**	**31.1±0.2**	**0.521**	**0.533**	**-2.8**

Overall, it is concluded that while regional delivery is highly repeatable in the lab, this is not the case for WHVC. Increased number of braking events and generally lower speeds over WHVC seem to affect the repeatability of this cycle in the dyno. VECTO SiCO mode is able to simulate Regional Delivery satisfactorily with a relatively low deviation (approximately 4%) from the measured value. This conclusion can be generalized as it was observed for all four vehicles tested.

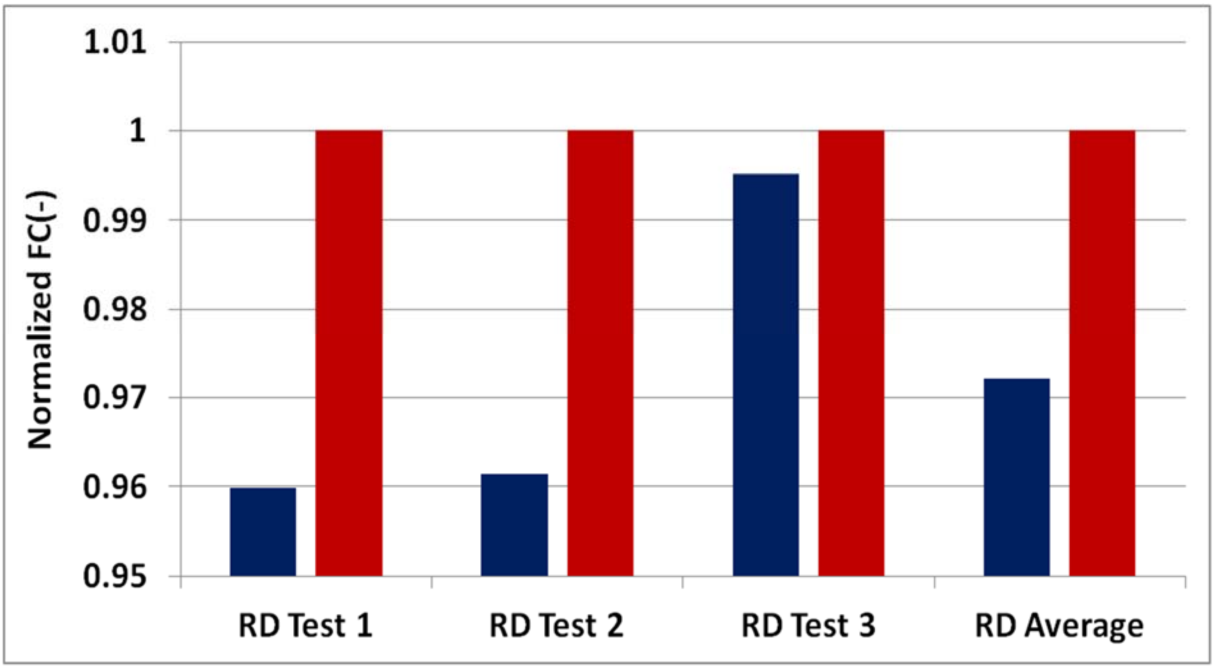

Figure 19: Normalized simulated (SiCO mode - blue bars) vs. measured (=1.0 – red bars) FC of vehicle #4 for Regional Delivery tests

3.2 On-road measurements

The scope of on-road tests was to check the repeatability of the applied methodology due to the high level of uncertainty compared to laboratory tests and to investigate the quality of the simulations under not controlled environment and operating conditions in order to obtain a broader picture of the simulator's accuracy. Overall, the aim was to test if ex-post verification based on on-road tests is possible and under what conditions.

3.2.1 Vehicle #1

Table 24 gives an overview of on-road test results without the application of any filter. In all cases measurements were conducted with A/C being switched off. All tests were performed with 30 min warming up of the vehicle and the first 15 min of the route were disregarded. This way a minimum of conditioning for the engine as well as for the gearbox and the axle was achieved as VECTO does not consider the cold behavior of the components. Tests were performed at an average temperature of 7.8±2.9°C and 45±9% RH without any form of precipitation. Values given in the last raw of Table 24 are averaged over the 3 selected measurements and ± values correspond to the SD of the 3 measurements. Specific fuel consumption is given normalized to the average of the 15 SiCO points value as g Fuel/kWh. The last column represents the relative standard deviation of the three measurements of fuel consumption (g Fuel/kWh) as measured at the shaft (coefficient of variation).

Table 24 clearly demonstrates that on-road tests proved to be highly repeatable. The coefficient of variation over the three different tests was lower than 1%. Unlike transient tests in the laboratory there are no specific difficulties for the driver to reproduce braking events over on-road tests due to the fact that the driving behaviour is more normal. All tests exhibited similar speed profile with average speed being close to 67 km/h. A difference in the energy consumed was observed in trip #3 compared to the other two trips but it did not affect the overall fuel consumption which was found to be similar for all trips.

Table 24: On-road test results for vehicle #1

Test	Average Speed [km/h]	Energy at Shaft Measured [kWh]	Normalized Specific FC at Shaft [g/kWh]	Relative SD [%]
On-Road #1	66.9	204.8	1.083	-
On-Road #2	66.4	205.9	1.066	-
On-Road #3	66.6	197.2	1.081	-
On-road Average	**66.6±0.3**	**202.6±4.7**	**1.077**	**0.9**

Table 25 presents the comparison between measured and simulated fuel consumption values over all on-road tests. Comparison is performed over normalized to the average of all measurements g Fuel/h value in order to better reflect the different FC over the whole range of points tested. Both VECTO SiCO and Engineering mode were tested and compared to the measured fuel consumption values. VECTO simulations were performed for all three selected tests. Values given in the last raw are averaged over the 3 measurements and ± values correspond to the SD of the 3 measurements. The deviation between measured and simulated values is also given in Figure 20.

Table 25: Measured vs. simulated FC over on-road tests for vehicle #1

Test	Average Speed [km/h]	Normalized FC VECTO SiCO Mode [g/h]	Normalized FC VECTO Eng. Mode [g/h]	Normalized FC Measured [g/h]	Deviation Measured vs. SiCO Mode [%]	Deviation Measured vs. Eng. Mode [%]
On-Road #1	66.9	0.481	0.451	0.467	3.1	-3.3
On-Road #2	66.4	0.486	0.446	0.459	5.8	-2.8
On-Road #3	66.6	0.475	0.451	0.452	5.1	-0.2
On-road Average	**66.6±0.3**	**0.481**	**0.449**	**0.459**	**4.7**	**-2.1**

As shown in Table 25 the average deviation between the measured on-road fuel consumption and the simulated one was calculated to be 4.7% with the VECTO SiCO mode and 2.1% with the VECTO Engineering mode. This is a very satisfactory figure and similar to that reported previously from Fontaras et al. (2016) with another Euro VI truck. The most accurate results were achieved with the Engineering mode which takes into account the road gradient but not the measured torque. On the other hand, SiCO mode exhibited a slightly higher deviation which is partly attributed to the offset due to torque drift as no correction was applied. This is clearly demonstrated in Figure 21 where second by second measured and simulated (SiCO mode) fuel consumptions are displayed. It is seen that the simulated fuel consumption is constantly increasing compared to the measured value with the time (green spotted area). A 2-3% overestimation of the measured torque at the shaft takes place and therefore is incorrectly fed to the simulator resulting in an overestimation of the simulated fuel consumption. Thus a correction should be applied for this reason making both modes equally capable of predicting the vehicle's fuel consumption.

Overall, it is seen that on-road tests proved to highly repeatable. There was a good agreement between measured and simulated values for both VECTO Engineering and SiCO mode. Furthermore it is seen that the VECTO tool seems to perform in a robust way as the coefficient of variation for the 3 measurements was found to be 1.1% for the SiCO mode and 0.6% for the Engineering mode. It is seen that ex-post verification based on on-road tests could be possible with the advantage of being able to cover all vehicle types. However, there is still a need to work on the details of the test protocol, define test boundary conditions and understand the differences found among the two different VECTO modes.

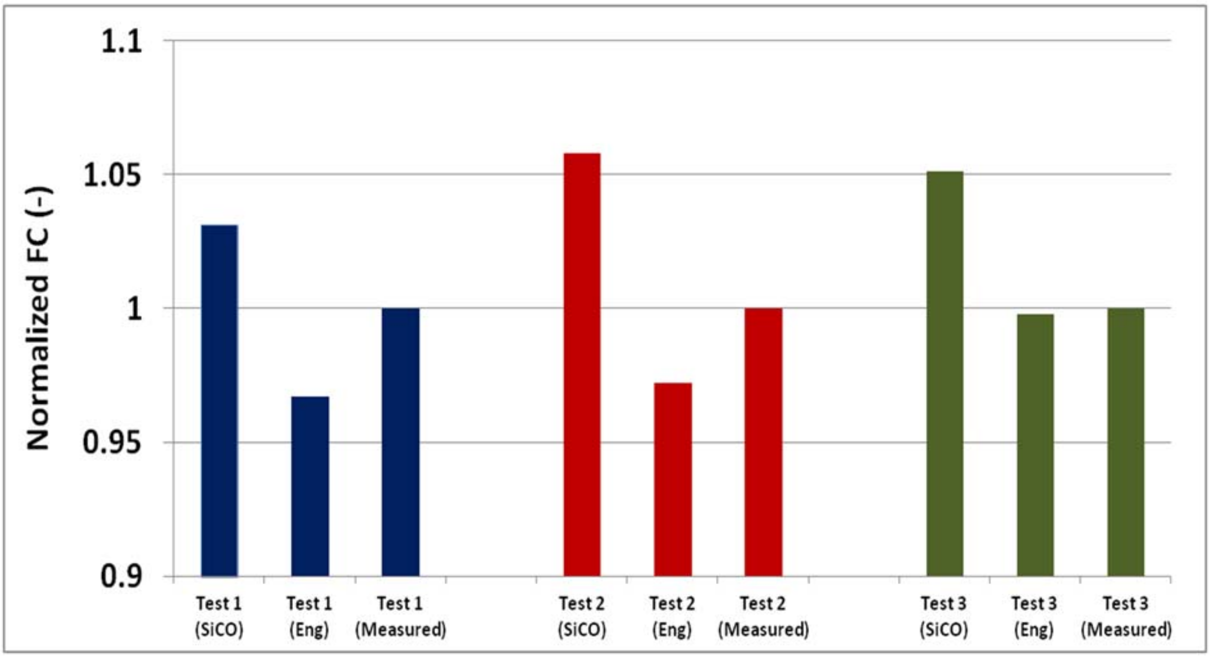

Figure 20: Normalized simulated vs. measured (=1.0) FC of vehicle #1 for on-road tests

Figure 22 shows the measured shaft power map for all different types of tests (i.e. on-road, regional delivery and steady state points) conducted with vehicle #1. It can be seen that SiCO test covers only a small part of the actual map and is more representative of medium and higher loads. Also it is seen that Regional Delivery is not highly representative of real-world operation as there are 2 main blocks of points which are not found in the RD cycle (one of 1080 RPM and another with 1280 RPM). Finally, it is apparent that under real-world conditions there are many low load points (i.e. <50 kW) making clear that they should also be tested during the SiCO test.

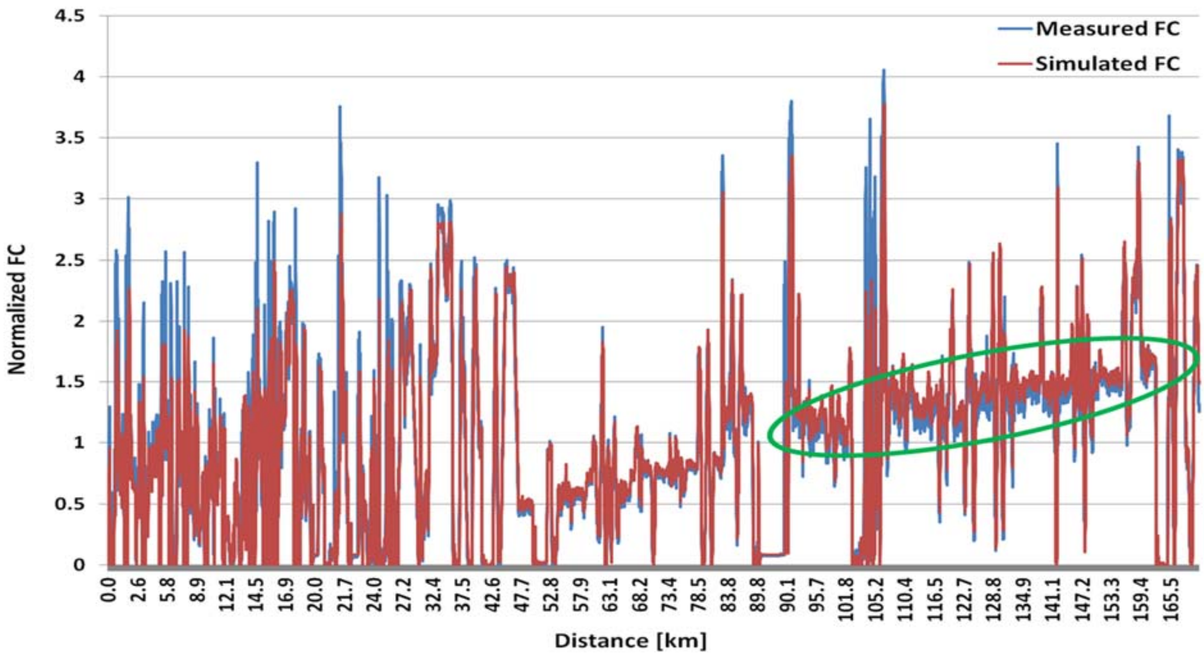

Figure 21: Real time normalized simulated vs. measured FC for on-road test 1 (vehicle 1)

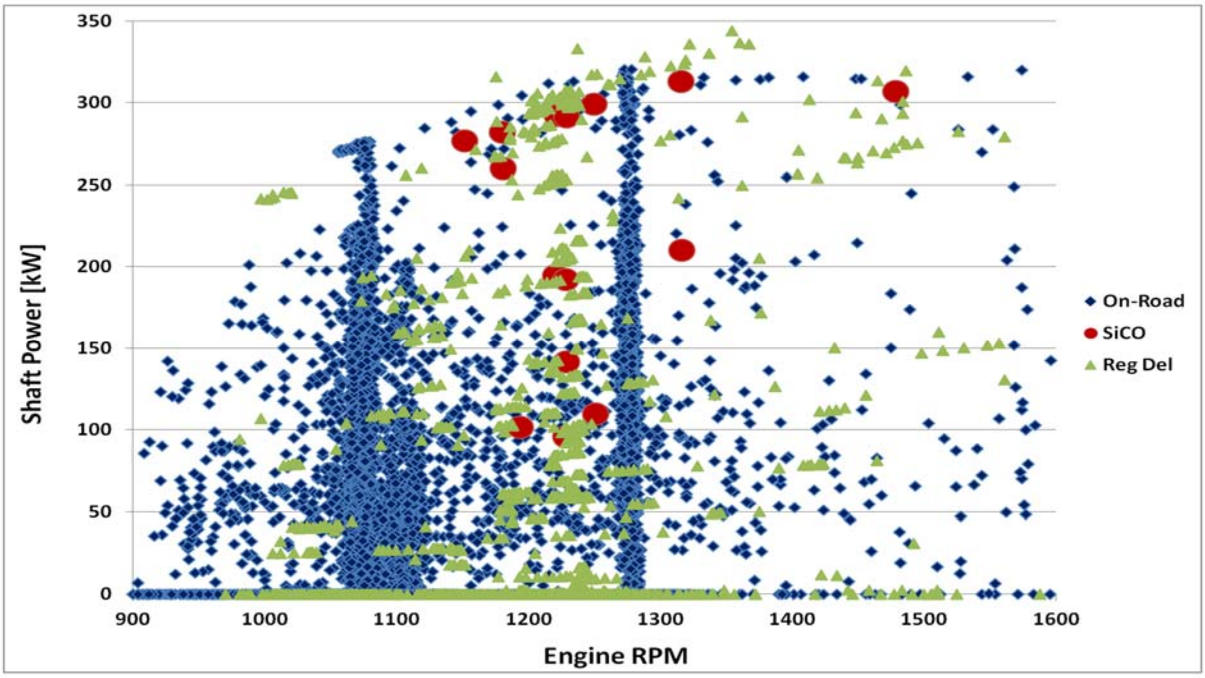

Figure 22: Shaft power map over on-road, Regional Delivery and SiCO tests

3.2.2 Vehicle #2

Table 26 gives an overview of on-road test results with vehicle #2. Among the four executed tests the two closest to the average fuel consumption value were selected for the processing of the results. No filters were applied and measurements were conducted with A/C being switched off. A minimum of conditioning for the engine, gearbox and the axle was achieved by a 30 min warming up of the vehicle. Also the 15 min of the route were disregarded. Tests were performed at an average temperature of 13.9±2.3°C and 42±16% RH without any form of precipitation. Values in the last raw are averaged over the 3 selected measurements with ± values corresponding to the SD of the 3 measurements. Vehicle specific fuel consumption is normalized to the average of the 17 SiCO points value as g Fuel/kWh. The last column represents the coefficient of variation of the 3 fuel consumption (g Fuel/kWh) measurements.

Table 26: On-road test results for vehicle #2

Test	Average Speed [km/h]	Wheel Energy Measured [kWh]	Normalized VSFC [g/kWh]	Relative SD [%]
On-Road #1	62.5	231.5	1.016	-
On-Road #2	62.9	231.3	1.002	-
On-road Average	**62.7±0.3**	**231.4±0.2**	**1.009**	**1.0**

Like in case of vehicle #1, it is seen from Table 26 that on-road tests can be highly repeatable. The coefficient of variation over the two different tests again did not exceed 1%. Both tests exhibited similar speed profile with an average speed of approximately 63 km/h while no significant difference in the consumed energy was observed. This is a very important finding and is confirmed for two different vehicles. It is demonstrated that on-road tests can be equally repeatable to chassis dyno tests allowing thus the ex-post verification procedure to be based on on-road potentially overcoming all drawbacks related to the laboratory testing.

Table 27: Measured vs. simulated FC over on-road tests for vehicle #2

Test	Average Speed [km/h]	Normalized FC VECTO w/o P_{add} [g/h]	Normalized FC VECTO 4.51kW P_{add} [g/h]	Normalized FC Measured [g/h]	Deviation Measured vs. w/o P_{add} [%]	Deviation Measured vs. P_{add} [%]
On-Road #1	62.5	0.549	0.577	0.569	**-3.6**	**1.4**
On-Road #2	62.9	0.558	0.586	0.565	**-1.4**	**3.6**
On-road Average	**62.7±0.3**	0.553	0.581	0.567	**-2.5**	**2.5**

Table 27 presents the comparison between measured and simulated fuel consumption values over on-road tests with vehicle #2. Comparison is performed over normalized to the average of all measurements g Fuel/h value. In this case only VECTO SiCO mode was tested. However, two different SiCO mode scenarios were applied (without P_{add} and with 4.51kW). Values given in the last raw are averaged over two measurements and ± values correspond to the SD of the two measurements. The deviation between measured and simulated fuel consumption is expressed both in g Fuel/h and g Fuel/kWh without any difference. The deviation between measured and simulated values is also depicted in Figure 23.

Table 27 demonstrates that the average deviation between the measured and the simulated on-road fuel consumption was found to be 2.5% with both VECTO SiCO modes. Once more this is a quite satisfactory figure with respect to these reported previously (Fontaras et al. 2016). In this case SiCO mode proved to be more accurate compared to vehicle #1 probably due to the use of the wheel torquemeter device. A zeroing and a correction based on the measured drift is applied before and after testing, therefore the simulated and measured fuel consumption do not deviate with the time like in case of vehicle #1. This is clear from Figure 24 where the real time normalized simulated and measured fuel consumption for on-road test 1 is shown. The difference in the performance of the two devices could satisfactorily explain the 2-3% more accurate simulation achieved with vehicle #2.

Once more on-road tests proved to be highly repeatable. A very good agreement between measured and simulated values for both VECTO SiCO modes was observed (deviation <3%). VECTO tool seems to be able to simulate the actual fuel consumption in a robust way as the coefficient of variation for the two simulations was found to be lower than 2%. It is seen that ex-post verification based on on-road tests could be possible with the advantage of being able to cover all vehicle types.

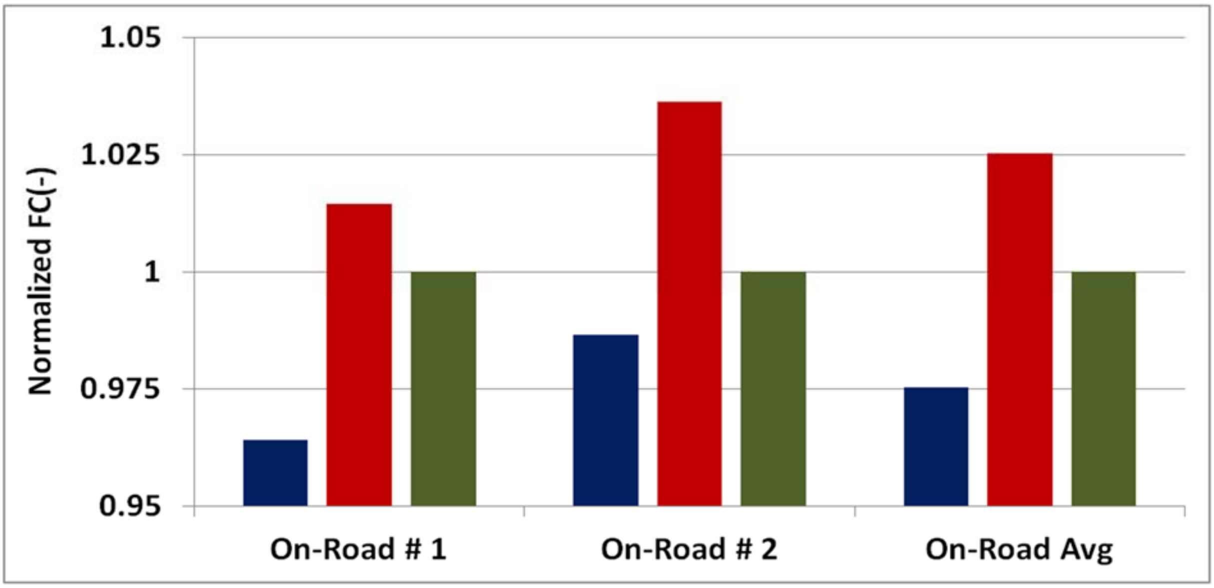

Figure 23: Normalized simulated vs. measured (=1.0) FC of vehicle #2 for on-road tests

Figure 25 depicts the measured wheel power map for all different types of tests conducted with vehicle #2. Like in case of vehicle #1, SiCO test covers only a small part of the actual map and is more representative of medium and higher loads. Regional Delivery cannot represent real-world operation very accurately as it is focused mainly in one block of points (at approximately 1170 RPM), thus leaving out several other important blocks where the engine actually operates. Once more it is demonstrated that under real-world conditions there are many low load points (i.e. <50 kW) making clear that they should also be taken into account for the SiCO test.

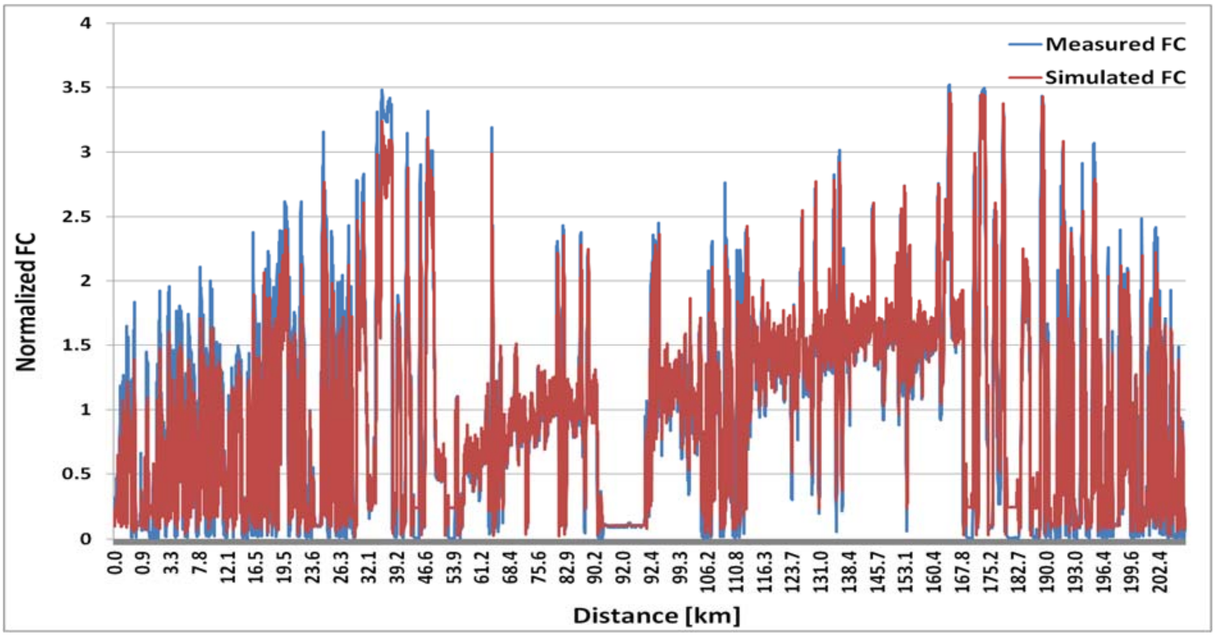

Figure 24: Real time normalized simulated vs. measured FC for on-road test 1 (vehicle 2)

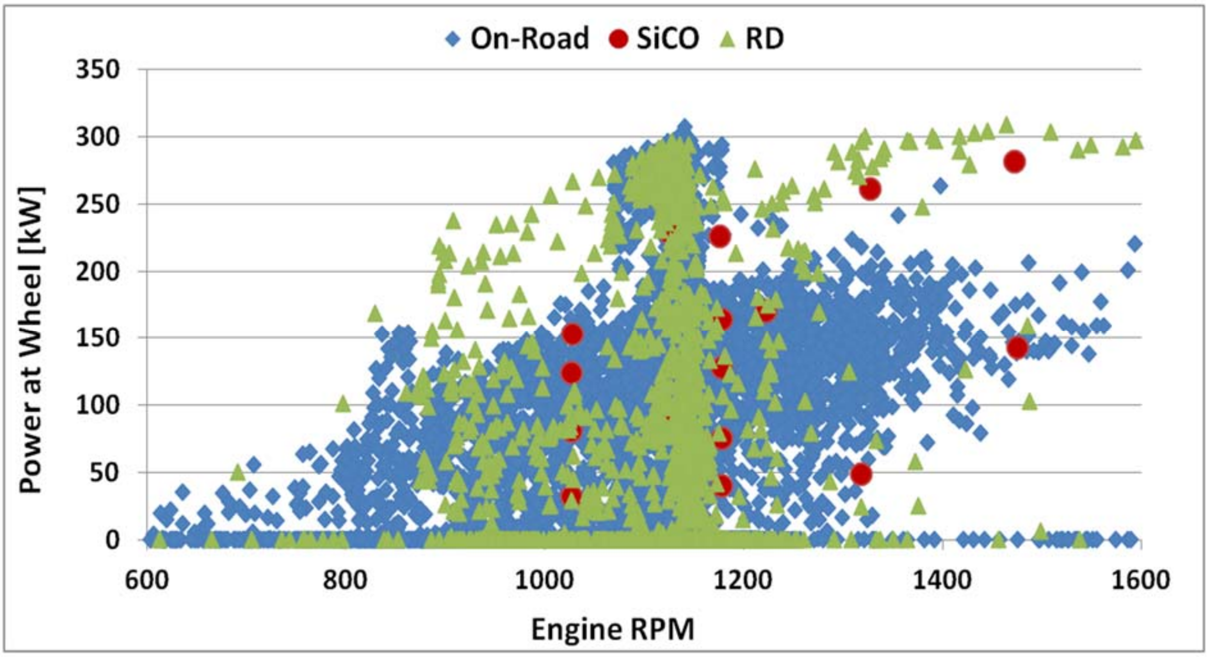

Figure 25: Wheel power map over on-road, Regional Delivery and SiCO tests

3.2.3 Vehicle #3

Table 28 gives an overview of on-road test results with vehicle #3. Values in the last raw represent the average over the 3 selected measurements while ± values correspond to the SD of the 3 measurements. No filters were applied and measurements were conducted with A/C being switched off. A minimum of conditioning for the engine, gearbox and the axle was achieved by a 30 min warm up of the vehicle. The first 15 min of the route were disregarded. Tests were performed at an average temperature of 25.5±0.7°C and 43±6% RH without any form of precipitation. Fuel consumption is normalized to the average value measured from the 16 SiCO points in g Fuel/kWh. The last column represents the coefficient of variation of the 3 fuel consumption (g Fuel/kWh) measurements.

Table 28: On-road test results for vehicle #3

Test	Average Speed [km/h]	Wheel Energy Measured [kWh]	Normalized VSFC [g/kWh]	Relative SD [%]
On-Road #1	69.3	145.5	1.056	-
On-Road #2	67.6	153.0	1.062	-
On-Road #3	69.5	149.6	1.071	-
On-road Average	**68.8±1.1**	**149.3±3.8**	**1.063**	**1.4**

It is one more confirmed that on-road tests can be highly repeatable. The coefficient of variation over the three different tests slightly exceeded 1% and was very close to the values found for vehicles #1 and #2. All tests exhibited similar speed profile with an average speed of approximately 69 km/h, while there was no significant difference in the measured wheel energy. It is clearly demonstrated with three different vehicles that on-road tests can be equally repeatable to chassis dyno tests, allowing thus the ex-post verification procedure to be based on real world testing.

Table 29: Measured vs. simulated FC over on-road tests for vehicle #3

Test	Average Speed [km/h]	Normalized FC VECTO SiCO Mode [g/h]	Normalized FC VECTO Eng. Mode [g/h]	Normalized FC Measured [g/h]	Deviation Measured vs. SiCO Mode [%]	Deviation Measured vs. Eng. Mode [%]
On-Road #1	69.3	0.552	0.793	0.560	**-1.4**	**-9.2**
On-Road #2	67.6	0.566	0.773	0.563	**0.6**	**-6.3**
On-Road #3	69.5	0.570	0.797	0.568	**0.4**	**-7.2**
On-road Average	**68.8±1.1**	**0.563**	**0.788**	**0.564**	**-0.2**	**-7.6**

Table 29 presents the comparison between measured and simulated fuel consumption values over the individual on-road tests with vehicle #3. Comparison is performed over normalized to the average of all measurements g Fuel/h value in order to better reflect the different FC over the whole range of points tested. Also the averaged values are provided in the last raw and ± values correspond to the SD of the three measurements. Both VECTO SiCO and Engineering mode were examined. Since also VECTO Engineering mode was used the deviation between measured and simulated fuel consumption is calculated using the fuel consumption at the wheel in g Fuel/kWh. The deviation between measured and simulated values is also depicted in Figure 26.

Table 29 shows that the average deviation between the measured and the simulated on-road fuel consumption was found to be 0.2% with VECTO SiCO mode. This practically means that VECTO can precisely simulate the fuel consumption for this particular truck. Again VECTO SiCO mode proved to be more accurate compared to vehicle #1, probably due to the use of the wheel torquemeter device instead of the torquemeter at the cardan shaft. It is shown in Figure 27 that simulated (VECTO SiCO mode) and measured fuel consumption do not deviate with the time like in case of vehicle #1. On the other hand, there is a high deviation between the measured and the simulated on-road fuel consumption with VECTO Engineering mode. This was also observed with the transient cycles in the lab and shall be further investigated.

Overall, on-road tests proved to be highly repeatable. A very good agreement between measured and simulated values for VECTO SiCO mode was observed. VECTO tool seems to be able to simulate the actual fuel consumption in a robust way as the coefficient of variation for the three simulations was found to be lower than 1%.

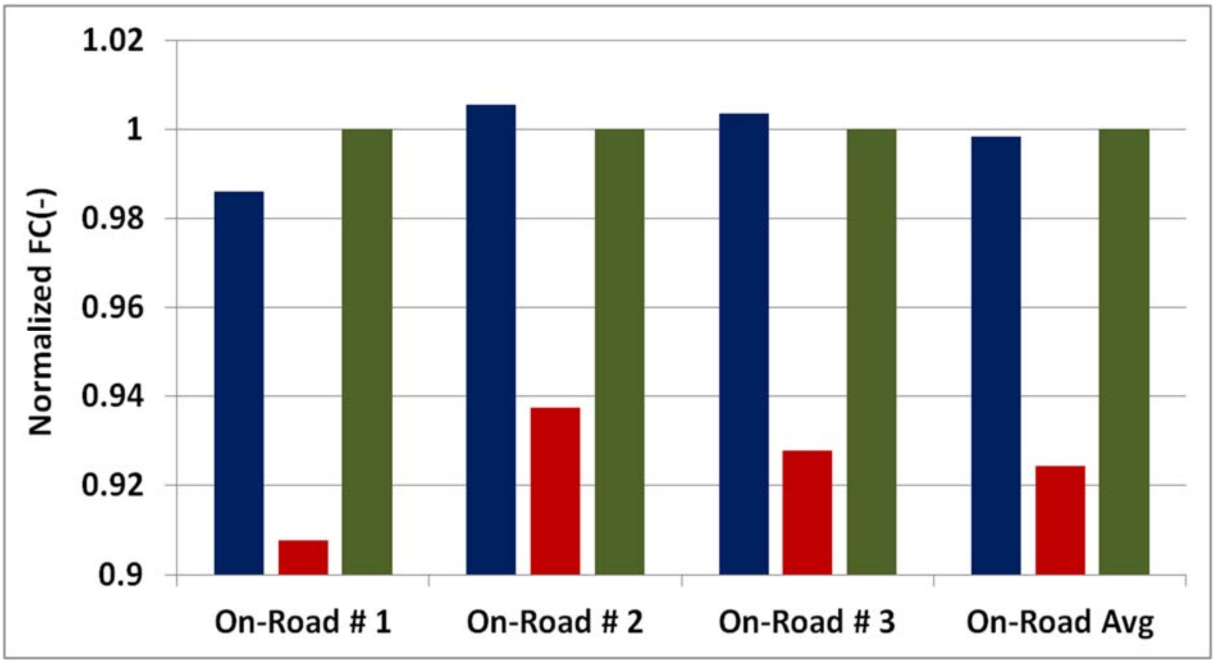

Figure 26: Normalized simulated vs. measured (=1.0) FC of vehicle #3 for on-road tests

Figure 28 depicts the measured wheel power map for all different types of tests conducted with vehicle #3. Like in case of the other tested vehicles, SiCO test covers only a small part of the actual map and is more representative of medium and higher loads. Regional Delivery cannot represent real-world operation very accurately as it is focused mainly in one block of points (at approximately 1400 RPM), thus leaving out several other important blocks where the engine actually operates (close to 1450 RPM). Once more it is demonstrated that under real-world conditions there are many low load points (i.e. <40 kW).

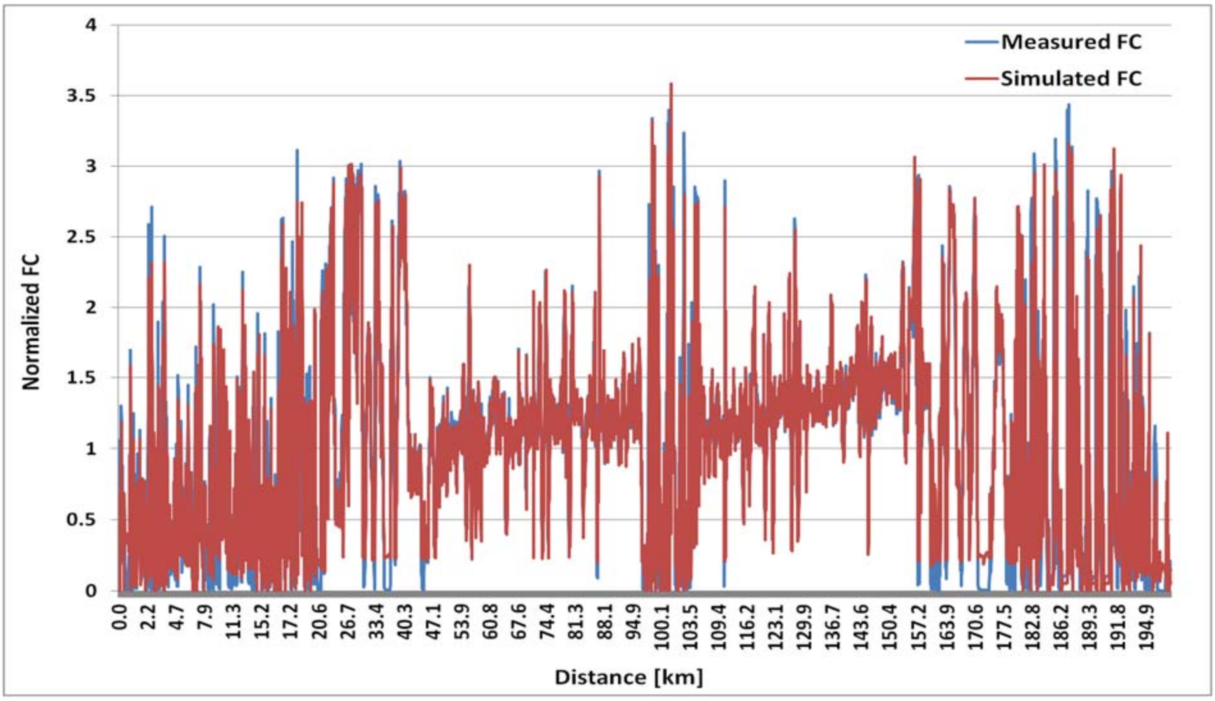

Figure 27: Real time normalized simulated vs. measured FC for on-road test 1 (vehicle #3)

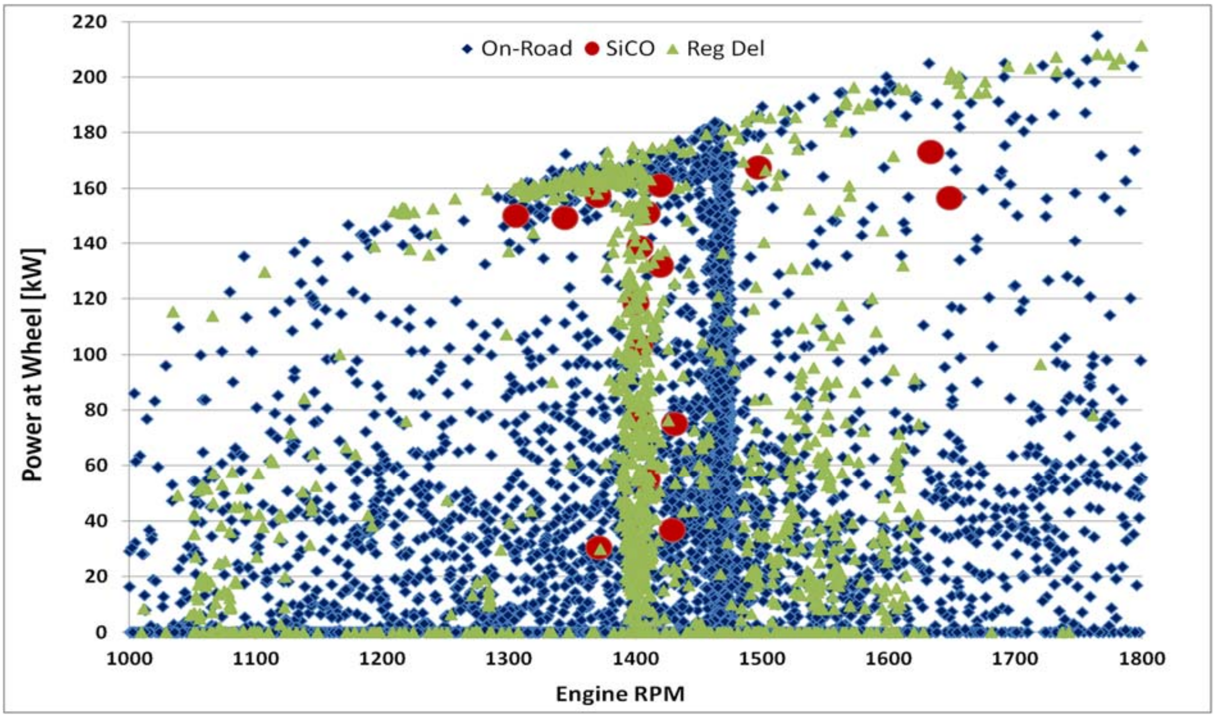

Figure 28: Wheel power map over on-road, Regional Delivery and SiCO tests

3.2.4 Vehicle #4

Table 30 gives an overview of on-road test results with vehicle #4. Unfortunately due to time restrictions only two tests were performed. No filters were applied and measurements were conducted with A/C being switched off. A minimum of conditioning for the engine, gearbox and the axle was achieved by a 30 min warming up of the vehicle. The first 15 min of the route were disregarded. Values in the last raw are averaged over the 2 measurements. Tests were performed at an average temperature of 28.0±1.7°C and 55±7% RH without any form of precipitation. Fuel consumption at the shaft is expressed in g Fuel/h and normalized to the average of the 18 SiCO points value as g Fuel/kWh. The last column represents the coefficient of variation of the two fuel consumption (g Fuel/kWh) measurements.

Table 30: On-road test results for vehicle #4

Test	Average Speed [km/h]	Wheel Energy Measured [kWh]	Normalized VSFC [g/kWh]	Relative SD [%]
On-Road #1	67.9	216.9	0.996	-
On-Road #2	69.6	213.1	1.001	-
On-road Average	**68.8±1.2**	**215.0±2.6**	**0.998**	**0.3**

Table 30 demonstrates that on-road tests with vehicle #4 showed an excellent repeatability. The coefficient of variation over the two different tests was lower than 1%. Individual tests exhibited similar speed profile with an average speed of approximately 69 km/h while no significant difference in the consumed energy was observed. Overall, the high repeatability of on-road tests is a very important finding and is confirmed for all tested vehicles. It is demonstrated that on-road tests can be equally repeatable to chassis dyno tests allowing thus the ex-post verification procedure to be based on on-road potentially overcoming all drawbacks related to the laboratory testing.

Table 31: Measured vs. simulated FC over on-road tests for vehicle #4

Test	Average Speed [km/h]	Wheel Energy Measured [kWh]	Normalized FC VECTO [g/h]	Normalized FC Measured [g/h]	Deviation Measured vs. SiCO Mode [%]
On-Road #1	67.9	216.9	0.466	0.483	**-3.5**
On-Road #2	69.6	213.1	0.477	0.489	**-2.6**
On-road Average	**68.8±1.2**	**215.0±2.6**	**0.471**	**0.486**	**-3.1**

Table 31 presents the comparison between measured and simulated fuel consumption values over on-road tests with vehicle #4. Comparison is performed over normalized to the average of all measurements g Fuel/h value. In this case only VECTO SiCO mode was tested. Values given in the last raw are averaged over the two measurements and ± values correspond to the SD of the two measurements. The deviation between measured and simulated fuel consumption is expressed in g Fuel/h. The deviation between measured and simulated values is also depicted in Figure 29.

Table 31 demonstrates that the average deviation between the measured and the simulated on-road fuel consumption was found to be approximately 3.0%. Once more this is a very satisfactory figure and comparable to that found for the other vehicles. Both individual trips exhibited similar difference. Also in this case SiCO mode proved to be more accurate compared to vehicle #1 probably due to the use of the wheel torquemeter device. Figure 30 presents the real time normalized simulated and measured fuel consumption.

Once more on-road tests proved to be highly repeatable. A very good agreement between measured and simulated values for VECTO SiCO mode was observed (deviation close to 3%). VECTO tool seems to be able to simulate the actual fuel consumption in a robust way as the coefficient of variation for the two simulations was found to be lower than 1%.

Figure 31 depicts the measured wheel power map for all different types of tests conducted with vehicle #4. Steady state test covers only a small part of the actual map while Regional Delivery cannot represent real-world operation very accurately as it is focused mainly in one block of points (at approximately 1170 RPM), thus leaving out several other important blocks where the engine actually operates (close to 1200 RPM). Also it is seen that under real-world conditions there is a big portion of low load points (i.e. <50 kW) making clear that they should also be taken into account when the SiCO test is executed.

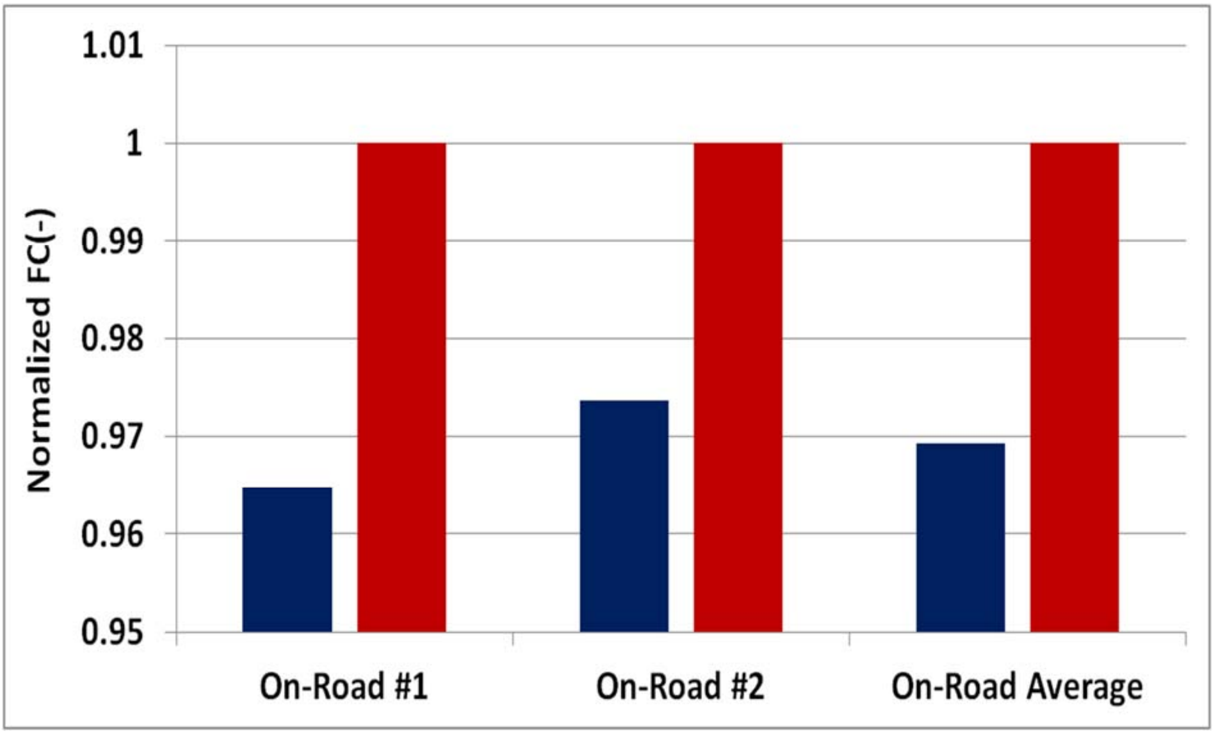

Figure 29: Normalized simulated vs. measured (=1.0) FC of vehicle #4 for on-road tests

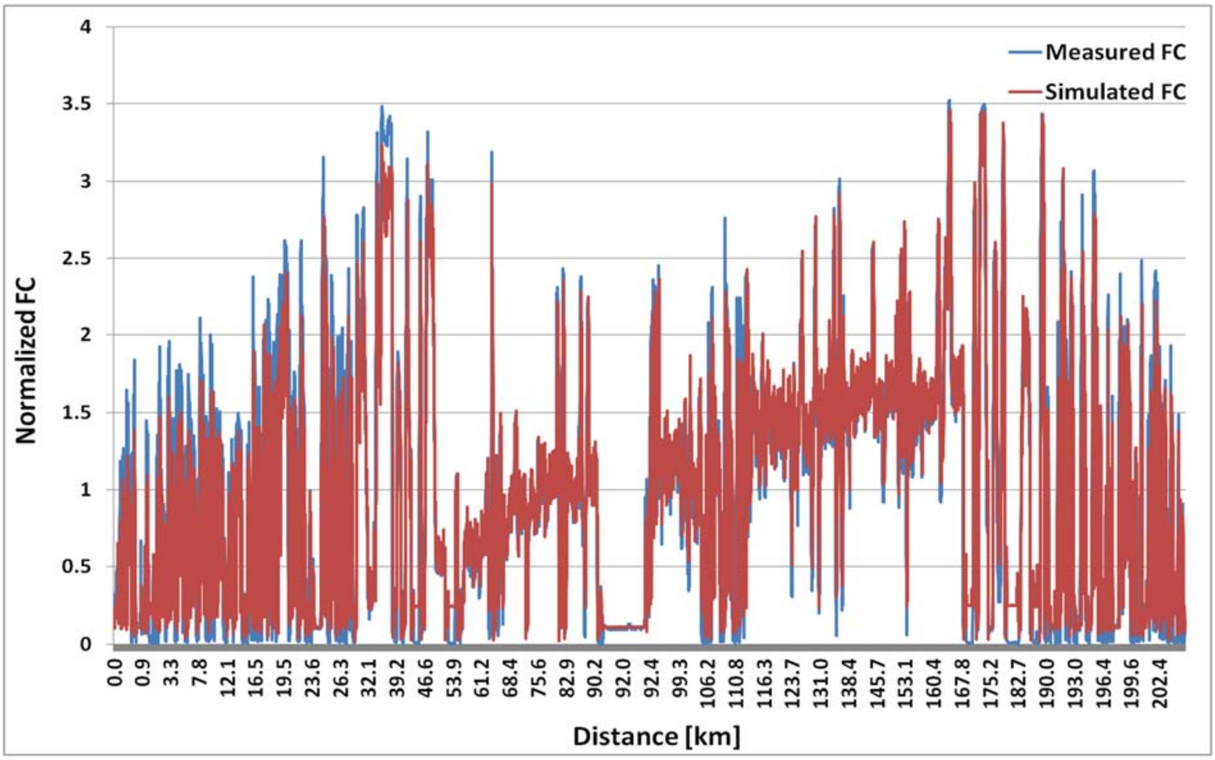

Figure 30: Real time normalized simulated vs. measured FC for on-road test 1 (vehicle 2)

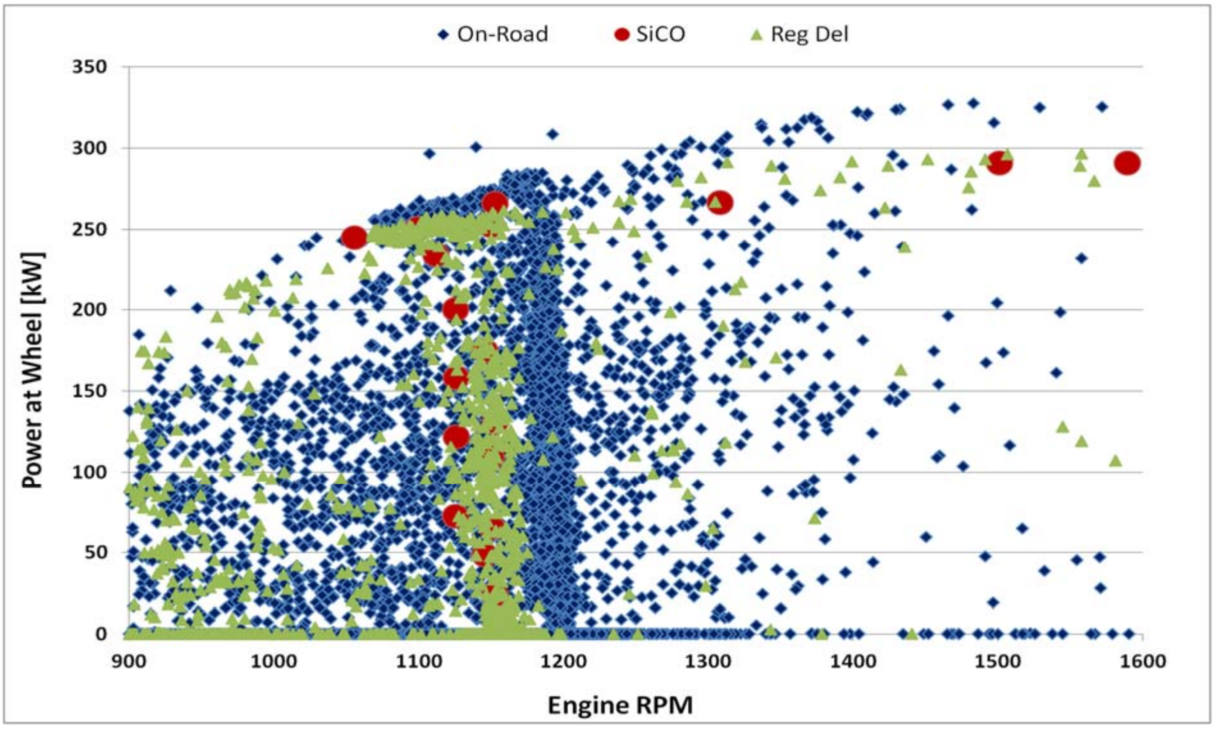

Figure 31: Wheel power map over on-road, Regional Delivery and SiCO tests

4 Conclusions

The study was conducted in two phases: the experimental phase which took place in JRC and involved testing of four Euro VI trucks in the laboratory and on-road, and the simulations phase which was performed within each individual OEM after the completion of the respective experimental campaign. Afterwards, JRC performed an independent comparison between the results of the simulations and those of the measurements and the conclusions were communicated to the respective OEM and to Member States at the 8th meeting of the CO_2 Heavy-Duty Editing Board. The findings of the main evaluation phase can be summarized to the following.

Option	Steady State Chassis Dyno	Transient Cycle Chassis Dyno	On-road operation
Repeatability	Very good except for low-load points	Very good	Very good
Representativeness of actual vehicle operation	Lowest	High with some restrictions in brake applications	Highest
Applicability to all HDVs	Restrictions for specific categories	Restrictions for specific categories	Possible
Cost	High	High	Lowest
Complexity	High due to the nature of the test	Low provided all equipment available	Low but requires specific test protocol
Test Data analysis	Lowest directly comparable to specific VECTO output	Low	High needs specific boundary conditions
Maturity (how close to actual implementation)	Good - A first draft of the protocol described	Poor - New protocol is required	Fair - Elements from PEMS protocol can be adopted

Steady State testing in the laboratory (SiCO)

- Steady state testing (SiCO test) proved to be satisfactorily repeatable in the laboratory in terms of fuel consumption, particularly when medium and high load points were examined (i.e. power at the wheel or shaft >100 kW). Low load points (i.e. power at wheel or shaft <50 kW) proved to be more difficult to repeat and thus more unstable compared to medium and high load points. This observation was confirmed by all OEMs and it needs to be considered seriously as important part of fuel consumption occurs over low load points. Furthermore, on-road tests demonstrated that low load points hold a significant share of the engine map under real world conditions; therefore they should not be neglected when investigating CO_2 emissions particularly of vehicle classes operating mostly in low vehicle speed conditions.

- A good agreement between measured and simulated fuel consumption values over medium and high loads was observed (deviation between measured and simulated fuel consumption in g/kWh was always lower than 2%) with two of the trucks tested. This was not the case for low load points (i.e. power at wheel or shaft <50 kW) where in some cases the deviation between measured and simulated fuel consumption reached 4%. On the other hand, vehicles #3 and #4 demonstrated generally higher deviations between measured and simulated fuel consumption values, regardless the tested load. Further investigation is required to understand the high deviations found for the two trucks.
- Apart from the issue with low load points there are several other drawbacks related to the SiCO test methodology. First of all, it is very difficult to cover the full engine and gearbox map with only 12 (or even 18) steady state points. Furthermore, it is not possible with one test to cover the full range of HD vehicles (trucks, buses, coaches, etc.). Finally, it needs expensive and difficult to maintain equipment, specifically when it needs to be performed on road (special braking trailers, dedicated testing facilities).

Transient testing in the laboratory

- The results showed good measurement repeatability (i.e. coefficient of variation for three fuel consumption measurements <2%) was observed in the laboratory when the Regional Delivery cycle was performed. Higher deviation was observed with the WHVC cycle for almost all vehicles (coefficient of variation close to 5%). Compared to Regional Delivery, WHVC speed profile includes many more braking events and is characterized from generally lower speeds. This could explain the lower repeatability of WHVC. Finally, normalized fuel consumption is found to be higher over the WHVC than the Regional Delivery probably due to the more transient nature of WHVC.
- A satisfactorily agreement of measured and simulated fuel consumption was observed over Regional Delivery tests with the deviation being generally lower than 3% and only once reaching 5%. VECTO P_{Wheel} mode proved to be more reliable in simulating measured fuel consumption values compared to Engineering mode whenever both modes were examined. On the other hand, WHVC proved to be more difficult to simulate accurately regardless the vehicle tested. In general, it could be concluded that VECTO is capable of providing reliable fuel consumption values in the laboratory over different transient tests within, however, a slightly higher uncertainty compared to steady state points.
- There are several drawbacks related to transient testing method in the laboratory. There are several difficulties for the driver to reproduce braking events over transient cycles and specifically over WHVC. Despite that the engine and gearbox map is more realistic and closer to the real world operation of the trucks it doesn’t yet cover the full range. Furthermore, it is not possible with one test to cover the

full range of HD vehicles (trucks, buses, coaches, etc.). Again there is a need for expensive and difficult to maintain equipment (chassis dyno, special braking trailers, etc.). Overall, it seems to be a poor compromise between steady state and on-road tests as it doesn't solve any issues related to neither of the two methods.

On-road testing

- Excellent fuel consumption repeatability was observed over on-road tests, regardless the truck tested. The coefficient of variation of fuel consumption measurements over three repetitions was always lower than 1.5%. This result is somewhat surprising since these tests were known to be quite uncertain and difficult to repeat accurately.
- Overall, a good agreement of measured and simulated fuel consumption values was observed over on-road tests with the deviation never exceeding <5%. When the wheel rims were used for the measurement of the torque at wheel the deviation between measured and simulated fuel consumption did not exceed 3%, while in the case of vehicle #1 it was found to be close to 5% due to the drift of the torquemeter installed at the cardan shaft. VECTO SiCO mode proved to be more reliable in simulating measured fuel consumption values compared to Engineering mode. Overall, it seems that VECTO is capable of providing reliable results over on-road tests. However, differences among different VECTO modes should be further investigated.
- On-road tests seem to be a good solution as they overcome most of the drawbacks related to laboratory testing methodologies. First of all, the full engine and gearbox map is investigated as the truck operates only under real world conditions. In this case one testing methodology with very limited modifications could be adopted to cover the full range of HD Vehicles. Finally, it overcomes the need for expensive equipment (chassis dyno, special braking trailers, etc.). Overall, the ex-post verification based on on-road tests is possible for trucks. However, there is a clear need to work on the details of the test protocol, define boundary conditions, and further understand the differences found among the different VECTO modes. Finally, it is necessary to define what would be considered as acceptable maximum deviation between measured and simulated values for CO_2 emissions.
- Regardless the testing methodology, a better agreement between measured and simulated fuel consumption values was observed when the wheel rims were used for the measurement of the wheel torque compared to the application of the cardan shaft torquemeter. This became more obvious over on-road tests due to their longer duration compared to laboratory tests.

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List of abbreviations and definitions

ACEA	European Automobile Manufacturers' Association
CLD	ChemiLuminescence Detector
CVS	Constant Volume Sampler
DPF	Diesel Particulate Filter
EC	European Commission
EFM	Exhaust Flow Meter
FC	Fuel Consumption
FTIR	Fourier Transform Infra-Red spectrometer
GPS	Global Positioning System
HDV	Heavy Duty Vehicle
HEPA	High Efficiency Particulate Air filter
HFID	Heated Flame Ionization Detector
JRC	Joint Research Centre
NDIR	Non-Dispersive Infra-Red sensor
NDUV	Non-Dispersive Ultra-Violet sensor
OBD	On-Board Diagnostics
PEMS	Portable Emissions Measurement System
PN	Particle Number
RD	Regional Delivery cycle
SCR	Selective Catalyst Reduction of NO_x
SiCO	Simplified Constant Speed Test
SS	Steady State
THC	Total Hydrocarbons
VECTO	Vehicle Energy consumption Calculation Tool
VSFC	Vehicle Specific Fuel Consumption
VELA	Vehicle Emissions Laboratories
WHTC	World Harmonized Transient Cycle
WHVC	World Harmonized Vehicle Cycle

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