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Development of Heavy Duty Vehicles CO_2 certification for Heavy Buses and Medium Lorries

Pilot Phase 2 – Validation of the Verification Test Procedure (VTP) for Buses and Medium Lorries Test Campaign Report

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Foreword

Policy context

In 2017, the European Commission (EC) adopted the Heavy-Duty Vehicle (HDV) CO_2 Certification Regulation on the determination of the CO_2 emissions and Fuel Consumption (FC) of HDVs (EU/2017/2400). In 2019, an appropriate verification procedure – to be applied randomly on complete vehicles after the certification processes – officially became a part of the HDV CO_2 Certification Regulation (EU/2019/318). The Verification Testing Procedure (VTP) consists of an on-road test to verify the CO_2 emissions of new vehicles after production. The provisions of the VTP test are described in detail in Annex Xa of EU/2019/318. In 2018, the EC launched a new regulatory initiative aiming at the development of a methodology for the certification of the CO_2 emissions and FC from HDVs and technologies not covered in the EU/2017/2400 regulation. The new methodology is intended to be a continuation of the current HDV CO_2 Certification Regulation and will be based on a combination of component testing and computer simulation of the vehicle's FC. An integral part of the extended CO_2 Certification Regulation will be the VTP test adapted for vehicles not covered in the existing regulation such as certain categories of Heavy Buses and Medium Lorries.

For the extension of the HDV CO_2 Certification Regulation to cover Heavy Buses and Medium Lorries, the EC launched in 2019 a series of experimental activities – Pilot Phases. Three different Pilot Phases have been scheduled. The main tasks of the Pilot Phase 1 (PP1) include the preparation of the draft technical annexes for the upcoming CO_2 certification regulation of HDVs not covered in EU/2017/2400, testing of new components with a focus on vehicle categories for which no experimental data are available, testing of the amended VTP procedure for vehicle categories not covered in EU/2017/2400, and a feasibility check of the proposed methodology for the inclusion of multistage vehicles. The Pilot Phase 2 is mainly dedicated to the inclusion of new technologies (WHR, Dual Fuel, Hybrids), whereas Pilot Phase 3 focuses on the development of an appropriate VTP procedure to cover hybrid and battery electric vehicles. Due to certain delays, some of the PP1 items were shifted to PP2. The whole experimental procedure is expected to be completed by the end of 2020. Details regarding the scheduling, execution and targets of the different Pilot Phases were provided at the 15th HDV CO_2 Editing Board meeting, whereas the updated version was analyzed at the 18th HDV CO_2 Editing Board meeting.

A fundamental part of the PP1 is the experimental validation of the amended VTP procedure for vehicle categories not covered in the existing CO_2 certification regulation. In this framework, DG-GROW requested JRC to launch a test campaign to investigate the validity, accuracy, and feasibility of the proposed methodology in the case of Heavy buses and Medium Lorries. Experiments were conducted on four Euro VI vehicles; two Medium Lorries and two Heavy Buses (in this case two Coaches). Tests were performed on-road following the specifications described in the draft Version of Annex Xa as communicated on 12.03.2020 on the EC CIRCABC[1]. The main goals of the experimental campaign were discussed at the 15th HDV CO_2 Editing Board meeting and can be summarized as follows:

- *Evaluate and validate the proposed changes to Annex Xa of Regulation (EU) 2017/2400 as published on the 12th of March 2020;*
- *Evaluate the capacity of VECTO tool to simulate CO_2 emissions over on-road transient tests for Medium Lorries and Heavy Buses;*
- *Evaluate different options for the VTP (i.e. shares urban/rural/motorway, transient conditions, etc.) for their influence on the accuracy of VECTO tool to simulate CO_2 emissions;*
- *Collect data to evaluate the feasibility of different options to monitor pollutant emissions during the VTP test.*

The last task of collecting data to evaluate different options for monitoring pollutant emissions during the VTP test has been decided to be addressed by a different group. Therefore, the current report will only provide collected data on pollutant emissions and will not go into the analysis of possible different options. These will be addressed by the HD CO_2 In-Service Verification group steered by DG-CLIMA.

[1] *https://circabc.europa.eu/ui/group/79f256f4-ca4c-41d4-a18f-69b92f81f728*).

Three vehicle manufacturers participated in this part of the PP1 (in alphabetical order Daimler, ISUZU and Van Hool) by providing the tested vehicles along with the necessary equipment and technical support. All tests were carried out under the responsibility of JRC.

Quick guide / Experimental

Four Euro VI certified vehicles – equipped with the state of the art of exhaust after-treatment systems – were tested for the purposes of the PP1. All tests were performed on-road over two alternative routes with different shares of urban, rural and motorway driving. Approximately 60% of the vehicles' maximum payload was applied in all cases. Vehicle #3 was tested also with an increased payload of 80%. All tests were conducted with the vehicles being warmed-up appropriately and under normal driving conditions. More details regarding the general provisions of the VTP test are provided later in the document and can also be found in the draft Annex Xa.

All vehicles were equipped with a mobile Fuel Flow Meter (FFM) to measure instantaneous fuel consumption according to EU/2019/318. The FFMs were different among the vehicles and were provided by the respective OEMs. Additionally, a Portable Emissions Measurement System (PEMS) was installed for the measurement of gaseous pollutant emissions (with specific attention to NO_x emissions). The PEMS system was similar in all tests and was provided by the JRC. The calculation of the wheel work output over each trip was based on the instantaneous wheel torque values measured by a dedicated torque measurement system. The Torquemeters were different among the vehicles and were provided by the respective OEMs. All settings influencing the auxiliary energy demand were set to a minimum or switched off where applicable.

A minimum of three on-road tests was conducted for each vehicle and route. Tests were performed during the same day but also over different days under slightly diverse climatic conditions. All tests that involved diesel particulate filter regeneration were completed as scheduled but not considered in the analysis. The primary comparison between the measured and simulated values was conducted using the FC recorded from the dedicated FFM devices. A secondary analysis was performed taking into account the PEMS CO_2 values with the aim of understanding possible deviations between the two instruments. Finally, gaseous pollutant emissions values were measured using the PEMS instrument.

All FC values provided in the report are normalized to the average FC of each vehicle separately. Thus, it is not possible to compare normalized FC values of different vehicles to understand the differences in their FC.

Results Analysis - Main findings

This part of the PP1 included four phases:

- *The preparation phase which took place between March and September of 2019. It included all necessary steps to prepare the vehicles and ship them to JRC fully equipped for the testing campaign.*
- *The experimental phase which took place between September 2019 and March 2020 at JRC. It involved testing four Heavy-Duty Euro VI vehicles following the guidelines described in the draft Annex Xa.*
- *The simulation phase which took place between May and September of 2020. In this phase, simulations were performed by the individual OEMs (or the JRC where applicable) following the guidelines described in the draft Annex Xa.*
- *The reporting phase which took place between July and October 2020. JRC presented the preliminary results to the 18th EB and contributed to the presentation of the overall PP results at the 19th EB. JRC also prepared the final technical report of the campaign.*

The manufacturers performed the simulations after the tests were finalized at JRC and without knowing the FC/CO_2 emissions results. Simulation results were then communicated to the JRC that 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 evaluation phase can be summarized as follows.

VTP Procedure and FC simulation

On-road tests were checked regarding their repeatability to understand the suitability of the proposed routes for each vehicle category. All on-road tests proved to be highly repeatable with the Standard Error (SE) for the Wheel Specific Fuel Consumption (WSFC) (measured with the FFM) not exceeding 2%. These results are in-line with the conclusions drawn during previous campaigns for other types of HDVs. For the two Coaches, a slightly larger SE for the WSFC was observed over Route #2, which can be attributed to its higher transient nature compared to Route #1. On the other hand, both Medium Lorries exhibited slightly larger SE for the WSFC over Route #1. Overall, and taking into account VECTO performance, Route #1, or a similar one, seems more appropriate for the VTP of Coaches, while Route #4, or a similar one, for the VTP of Medium Lorries. In any case, differences in the repeatability were not statistically significant. City buses have not been tested due to lack of availability of such vehicles. The increase of the payload from 60% to 80% did not affect the test repeatability for Medium Lorries. All other elements of the draft Annex Xa seem to be appropriate for the VTP of the discussed vehicle categories.

Regarding the comparison between the measured (FFM) and simulated (VECTO) FC values, different trends are observed. On one hand, both Coaches showed a quite good agreement between the measured and simulated FC with the deviation not exceeding 5.5%. These values are lower than the ones previously reported in the literature. The deviation over the less transient Route #1 was approximately 3% in 7 out of 8 total tests. The more transient Route #2 exhibited slightly higher deviations with 3 out of 6 tests being close to 5%. It seems that Route #1, or a similar one, is more appropriate for the VTP of this vehicle category also in terms of VECTO capability to reproduce real-world FC. The C_{VTP} for both vehicles did not exceed 1.060 in any of the 14 tests and fulfilled the pass criterion defined in EU/2019/318 for other vehicle categories. Medium Lorries exhibited a different behaviour compared to Heavy Buses. In all tests VECTO overestimates FC contrary to what is observed for the Heavy Buses. The average overestimation of Vehicle #4 is close to 4% over Routes #1 and #4. This is attributed to the overestimation of the electrical power demand of auxiliaries by the generic values in VECTO compared to the actual electrical power demand during the VTP test. However, the deviations for Vehicle #3 were up to 15%. The much higher deviations can be attributed to the component input data used in the simulations, that was not measured according to the official measurement procedures set out in (EU) 2017/2400. In both cases, JRC simulations with more realistic auxiliary power consumption led to significant improvement.

FC and CO_2 measurements

FC data measured by means of different instruments have been analysed to understand their suitability to provide accurate FC measurements. The FC calculated from the PEMS CO_2 emissions as well as ECU FC were compared against the reference FFM FC. The FC calculated from the PEMS CO_2 emissions was generally close to the corresponding FFM FC. The averaged deviation did not exceed 4%, except for Vehicle #4 on Route #4 which; however, did not give consistently repeatable PEMS measurements. Minor differences were observed in the deviations among the two routes, regardless of the tested vehicle. Practically, the PEMS seems to perform equally well both under non-transient and highly transient conditions. The ECU FC seems to be less accurate compared to the PEMS FC. Deviations for Vehicles #1, #2 and #3 were at the level of 3-4% following the trends described in the literature. However, Vehicle #4 exhibited significantly higher deviations reaching up to 10%. This could be attributed to the installation of the FFM in the fuel lines that introduced a pressure drop in the feed line and a higher backpressure in the return line. In general ECU calculated fuel consumption under non-transient and transient conditions matched well to the measured fuel consumption.

Pollutant Emissions

Initially, one of the goals of the current study was to collect experimental data to support analysis of how to monitor pollutant emissions during the VTP test. However, this task is being addressed by a different group under DG-CLIMA. Thus, the current report will only provide collected data of pollutant emissions and will not go into the analysis of possible different options. NO_x emissions were generally low and did not exceed the EURO VI engine certification limit (0.46 g/kWh). It is important to note that NO_x measurements were conducted under the warm operation of the engine and the aftertreatment system, thus it is expected that the catalyst would be fully effective and emissions would be low. The more transient Routes #2 and #4 show generally higher NO_x emissions pointing to a less effective operation of the catalyst under these conditions. It is noteworthy that Vehicle #1 exhibited very low NO_x emissions over both routes, thus the slight difference among the two routes lies within the experimental uncertainty. For this analysis to be complete there is a need to also measure NH_3 emissions. Finally, CO emissions were generally low and well below the EURO VI engine certification limit (4.0 g/kWh).

Related and future JRC work

JRC presented the results of the campaign to the 18th and 19th HD CO_2 Editing Board along with the main outcomes and proposals regarding the final version of Annex Xa. JRC will support DG-GROW in all future steps concerning the HDV CO_2 certification of Buses and Medium Lorries.

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Abstract

In 2019, a Verification Test Procedure (VTP) – to be applied randomly on complete vehicles after the certification processes – became a part of the HDV CO_2 Certification Regulation (EU/2019/318). The VTP consists of an on-road test to verify the CO_2 emissions of new vehicles after production. At the same time, a new regulatory initiative aiming at the certification of the FC from HDVs not covered in EU/2017/2400 was initiated. The new methodology will also include a VTP test; however, adapted for vehicle categories such as Heavy Buses and Medium Lorries. In this framework, DG-GROW requested JRC to launch a test campaign to investigate the validity, accuracy, and feasibility of the proposed methodology for these vehicle categories. Experiments were conducted on four Euro VI HDVs; two Heavy Buses and two Medium Lorries. All on-road tests proved to be highly repeatable with the SE for the WSFC not exceeding 2%. Both Coaches showed a quite good agreement between the measured and simulated WSFC with the deviation not exceeding 5.5%. Medium Lorries exhibited a different behaviour mainly due to the overestimation of the electrical power demand of auxiliaries by VECTO in the VTP Mode. Overall, a less transient route, similar to the regulated, seems more appropriate for the VTP of Coaches. On the other hand, a more transient route might be more suitable for the VTP of Medium Lorries. Increasing the payload from 60% to 80% does not seem to affect the test repeatability. The C_{VTP} for both vehicles fulfilled the pass criterion defined in 2019/318 for Heavy Lorries in all 14 tests. The FC data were analyzed to understand the suitability of different instruments to provide accurate FC measurements. The FC calculated from the PEMS CO_2 emissions is generally close to the reference FFM FC with the averaged deviation not exceeding 4% in the vast majority of the tests. The ECU FC seems to be slightly less accurate compared to the PEMS FC. Both PEMS and ECU seem to perform equally well both under non-transient and highly transient conditions. Finally, one of the goals of the study was to collect experimental data of pollutant emissions during the VTP test. NO_x emissions were generally low and did not exceed the EURO VI engine certification limit (0.46 g/kWh). The more transient routes exhibited higher NO_x emissions pointing to a less effective operation of the catalyst under these conditions. CO emissions were generally low and well below the EURO VI engine certification limit (4.0 g/kWh).

1 Introduction

In 2013, the European Union set targets to reduce its greenhouse gas emissions [1]; however, these targets have been revised to become stricter [2]. More specifically, in 2020, the European Commission will present an impact assessed plan to increase the EU's greenhouse gas emission reductions target for 2030 to at least 50% compared to 1990 levels. Since road transport is responsible for about 25% of the total CO_2 emissions in the European Union [3], CO_2 emission reduction targets have been set for most of the new vehicle types, including HDVs [4]. The introduction of the European Commission regulation for the determination of the CO_2 emissions and FC of HDVs [5], as well as the establishment of the respective simulation-based CO_2 quantification methodology, has been a fundamental step for the quantification of CO_2 emissions from HDVs, and will contribute towards curbing CO_2 emissions in the long term. However, EU/2017/2400, as well as its amendment Commission Regulation (EU) 2019/318 [6], cover only certain HDV categories (Heavy Lorry Classes 4, 5, 9 and 10) and not the entire EU HDV fleet. For that reason, the EC has initiated a series of projects to establish a comprehensive, standardized and accurate method to quantify the CO_2 emissions from all HDV categories. At the same time, a series of initiatives have been launched to extend the HDV CO_2 certification regulation to all relevant HDV categories.

HDVs are highly customizable, therefore the approach that best fits the particularities of the sector should be based on a combination of component testing and computer simulation. Standardized measurement of vehicles – or their components – is required and considered fundamental for building accurate and reliable models. The Vehicle Energy consumption Calculation TOol (VECTO) has been developed to be used for that purpose [7]. The VECTO tool was first launched in 2012, and has since then undergone various updates to become the official tool to be used for the certification of HDV CO_2 emissions in the EU [8]. In this model, the FC is simulated based on vehicle longitudinal dynamics. Input data regarding the vehicle, its driveline, and engine characteristics are supplied in order to simulate their performance over given operating conditions. More details regarding the tool and its capabilities can be found in the VECTO manual and in [9]. The plausibility of such a simulation-based approach had been assessed for different categories of Heavy Lorries (Trucks, Buses and Coaches) through three extensive experimental campaigns conducted by the JRC. The studies provided experimental data for supporting the plausibility of the simulation-based approach and were used for supporting the establishment of different elements of the HDV CO_2 certification regulation and its amendment [10-11].

Commission Regulation (EU) 2019/318 included for the first time a verification test procedure to be applied randomly on complete vehicles after the certification processes. The VTP consists of an on-road test to verify the CO_2 emissions of new vehicles after production and applies to certain HDV categories (Heavy Lorry Classes 4, 5, 9 and 10). A detailed description of the VTP test is provided in the Annex Xa of the Commission Regulation (EU) 2019/318 [6]. Following the European Commission regulatory initiative aiming at the extension of the certification regulation, the VTP test needs to adapt to other HDV categories not considered previously such as Heavy Buses and Medium Lorries. The nomenclature for the HDV sub-categories is defined in Table 1. For that reason, a part of the experimental activities launched by the European Commission to support the extension of the Certification regulation – also known as Pilot Phases – is dedicated to the testing of the amended VTP procedure for vehicle categories not covered in the existing CO_2 certification regulation.

Table 1. *Nomenclature for the HDV sub-categories*

HDV sub-category	Description
Light Lorry	N1 and N2 not exceeding 5 tons maximum mass with engine type approval according to Regulation (EU) 595/2009 and a reference mass exceeding 2610 kg
Medium Lorry	N2 exceeding 5 tons and not exceeding 7.4 tons maximum mass with engine type approval according to Regulation (EU) 595/2009 and a reference mass exceeding 2610 kg

Heavy Lorry	N2 exceeding 7.4 tons maximum mass and N3 with engine type approval according to Regulation (EU) 595/2009
Light Bus	M1 and M2 not exceeding 5 tons maximum mass with engine type approval according to Regulation (EU) 595/2009 and a reference mass exceeding 2610 kg
Medium Bus	M3 not exceeding 7.4 tons[1] maximum mass with engine type approval according to Regulation (EU) 595/2009
Heavy Bus	M3 exceeding 7.4 tons[1] maximum mass with engine type approval according to Regulation (EU) 595/2009

([1]) Not yet decided if 7.4t or 7.5t will be the appropriate threshold value for Buses
Source: JRC, 2020

Experiments were conducted on-road with four Euro VI vehicles; two Heavy Buses (Coaches) and two Medium Lorries (Rigid Lorry and Van). The present report summarizes the main conclusions from the application of the proposed changes to the draft Annex Xa as published on 12 March 2020. Furthermore, the present report discusses for the first time the accuracy of the VECTO tool to simulate CO_2 emissions over on-road transient tests for Medium Lorries. Finally, data to evaluate the feasibility of different options to monitor pollutant emissions during the VTP test were collected.

2 Experimental Methods

The experimental campaign took place between September 2019 and March 2020. The FC measurements included on-road VTP tests as prescribed in the draft Annex Xa which sets out the requirements for the Verification Testing Procedure of Heavy Buses and Medium Lorries[2]. Detailed descriptions of the tested vehicles, applied protocols and test conditions are provided in this chapter.

2.1 Test Vehicles

Four vehicles taken from series production were tested for the present study (Figure 1). Two Medium Lorries with different characteristics (N2 vehicles exceeding 5 tons and not exceeding 7.4 tons Technically Permissible Maximum Laden Mass (TPMLM) with engine type approval according to Regulation EU/595/2009 and a reference mass exceeding 2610 kg) and two Heavy Buses (Coach – M3 vehicles exceeding 7.4 tons TPMLM with engine type approval according to Regulation EU/595/2009) were tested.

Vehicles were in series conditions as typically delivered to the customer. All vehicles were provided by the respective OEMs in their standard operating conditions. No changes in hardware, such as lubricants, or in the software, such as auxiliary controllers, were applied to the vehicles according to the testers' knowledge. Some general information regarding the specifications of the vehicles is provided in Table 2. Figure 1 illustrates the vehicles tested in the current exercise.

Figure 1. Tested vehicles

Source: JRC, 2020

[2] https://circabc.europa.eu/ui/group/79f256f4-ca4c-41d4-a18f-69b92f81f728

Table 2. *Main vehicle specifications*

Characteristic	Vehicle #1 (Coach)	Vehicle #2 (Coach)	Vehicle #3 (Medium Lorry)	Vehicle #4 (Medium Lorry)
Engine Displacement [cm^3]	10677	10837	2143	2999
Rated Power [kW]	315	330	120	110
Gearbox [-]	AMT	AMT	MT	MT
Max load [kg]	19500	20000	5000	5500
Test Mass [kg]	16780	16560	4020 / 4520	4460
Percentage Load [%]	60	60	60 / 80[1]	60
Emissions Category	EURO VI c	EURO VI c	EURO VI d	EURO VI
Exhaust emissions control	EGR, DPF, SCR	EGR, DPF, SCR	EGR, DPF, SCR	EGR, DPF, SCR
Torque Measurement	Kistler Wheel Torque Sensors	ZF Half Shaft Torque Sensors	Kistler Wheel Force Sensors	Half Shafts Torque Sensors
Wheel speed Measurement	ABS sensor	ZF Wheel Speed Sensor	Kistler Wheel Speed Sensor	ABS sensor
FC Measurement	FFM – PEMS – ECU	FFM – PEMS – OBD	FFM – PEMS – ECU	FFM – PEMS – OBD

([1]) Vehicle #3 was tested under two different loads, 60% and 80%.
Source: JRC, 2020

For the calculation of the Wheel Specific Fuel Consumption (WSFC), the total work output of the driveline system (positive or absolute) was calculated from the torque and rotational speed of each driven wheel measured by the measurement devices installed at the wheels or drivetrain. Each vehicle featured a different torque measurement device with different specifications and characteristics (Table 2). Some devices also measured the rotational wheel speed. If this was not the case, the rotational wheel speed signal from the ABS was obtained from the vehicle's Controller Area Network (CAN). Additional signals, when available, were logged from the CAN and the On-Board Diagnostics (OBD) port. These include the ***engine speed***, the ***engine torque***, the ***fuel consumption***, the ***engaged gear*** (AMT transmissions only), the ***air compressor status*** (buses only), the ***fan speed*** and the ***vehicle speed***. The air compressor signal was not available for Vehicle #2. An estimate was used based on the nominal activation time during motorway and non-motorway driving. For each vehicle, the FC from the dedicated FFM devices was applied for the calculation of the WSFC. A secondary analysis was performed using the PEMS CO_2 emissions values to record deviations between the two instruments; FFM and PEMS. Finally, signals from the CAN ports were registered for additional analysis.

2.2 Test Cycles

VECTO contains a series of mission profiles used by the tool in order to simulate a realistic driving scenario. The driving cycles are distance-based, which means that the vehicle travels over a route and attempts to reach a target speed that depends on the route's segment. However, for various reasons, it is not possible to replicate a distance-based speed cycle on-road. Instead, well predefined routes were selected and executed for each vehicle. According to the draft Annex Xa, it is suggested to drive three routes for all new groups to be included in the certification regulation. The first route shall follow the parameters for vehicle groups 4, 5, 9 and 10 as in the Annex Xa of the Commission Regulation (EU) 2019/318 [6]. The second route shall follow the parameters for the actual vehicle group close to the "minimum" (or slow) targets boundaries according to Table 3 (i.e. maximum for urban and rural and minimum for motorway). The third route shall follow the parameters for the actual vehicle group close to the "maximum" (or fast) targets boundaries according to Table 3 (i.e. minimum for urban and rural and maximum for motorway). All shares shall be calculated distance based rather than time-based.

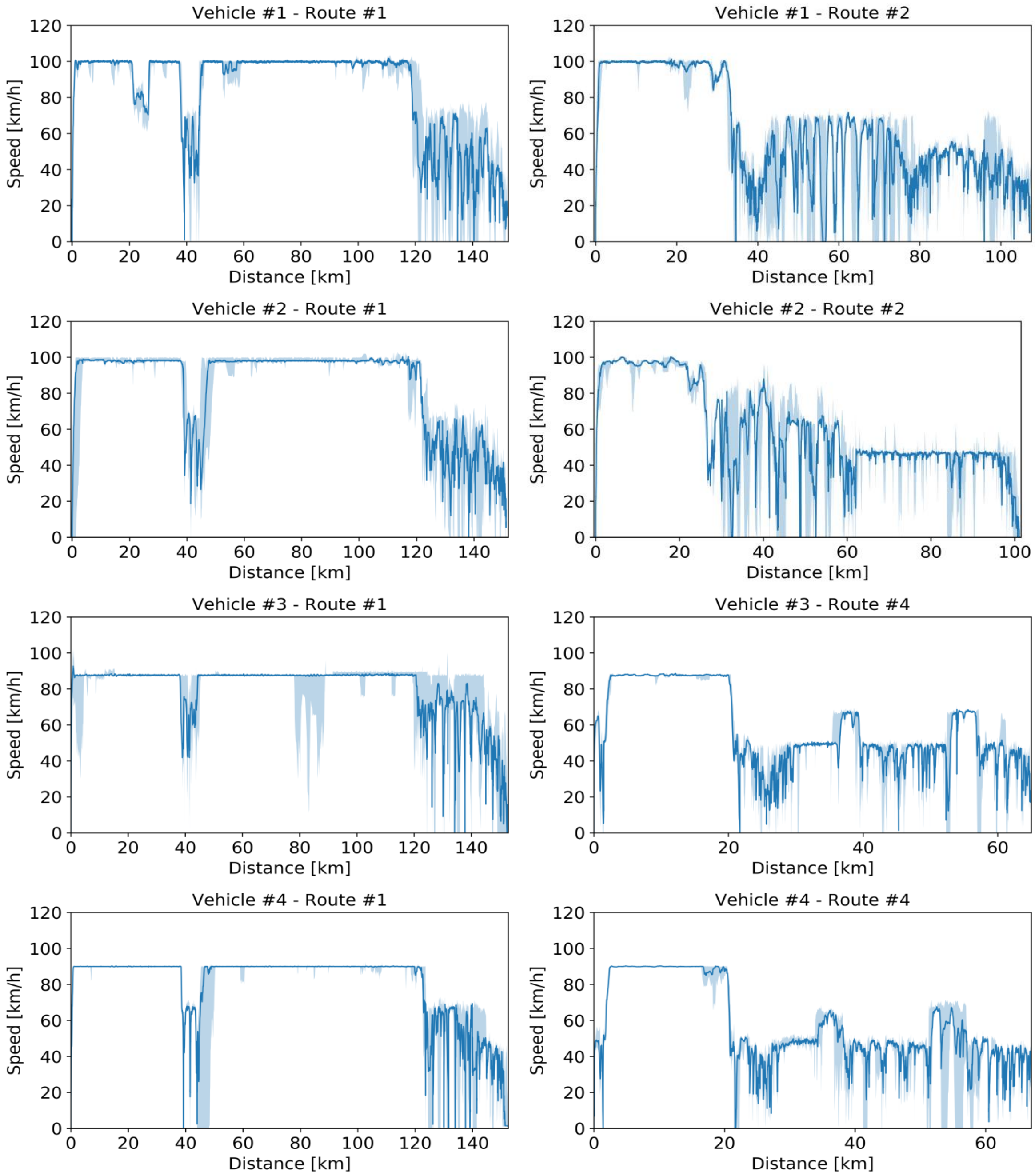
Table 3. *Parameters for valid VTP tests for different vehicle categories*

Vehicle Category	Heavy Lorries (Groups 4, 5, 9, 10)		High Floor Heavy Buses		Other Heavy & Medium Lorries	
Parameter	Min	Max	Min	Max	Min	Max
Route Identification	Route #1 (R#1)		Route #3 (R#3)	Route #2 (R#2)	Route #5 (R#5)	Route #4 (R#4)
Urban Share (Distance based)	**2%**	**8%**	12%	**40%**	10%	**50%**
Rural Share (Distance based)	**7%**	**13%**	10%	**30%**	15%	**25%**
Motorway Share (Distance based)	**74%**	**-**	25%	**-**	10%	**-**
Idling at standstill (Time based)	**-**	**5%**	-	**10%**	-	**10%**

Source: JRC, 2020

Based on the classification provided in Table 1, Vehicles #1 and #2 belong to High Floor Heavy Buses. Route #1 was designed to fulfil the (EU) 2019/318 and applies to all vehicles including Vehicles #1 and #2. Route #2 shall follow the "minimum" (or slow) target specification and shall include a high share of transient conditions. More specifically, Route #2 was designed to fulfil the provision of ~40% urban, ~30% rural and <25% motorway shares (distance-based) with standstill phase not exceeding 10% (time-based). ***Route #3 was not applied as it has similar specifications with the first route.*** Eventually, Route #1 of a total distance of approximately 150 km, as well as a more transient Route #2 of about 110 km, were applied for Vehicles #1 and #2. In the case of Vehicle #2, Route #2 was shortened due to road closures. As a result the share of rural driving slightly decreased in favour of the urban share. Furthermore, there is a difference in the last 40 km of Route #2 when applied by the two vehicles (Figure 2). This reflects the differences in the traffic lights encountered by the two vehicles and may influence the overall VTP accuracy. Figure 2 shows the mean speed trace of Vehicles #1 and #2 over the described routes for the different repetitions (the light blue band illustrates the minimum and maximum vehicle speed for different repetitions).

Figure 2. Mean speed trace of each vehicle over all routes



Source: JRC, 2020

Table 4 summarizes some basic statistics for the different routes (averaged over all trips for each vehicle and route). Red cells indicate shares slightly deviating from the limit values of Table 3. Indeed, it might take multiple runs until a suitable track to have the measurement completely compliant is found. The different routes are depicted in Figure 3.

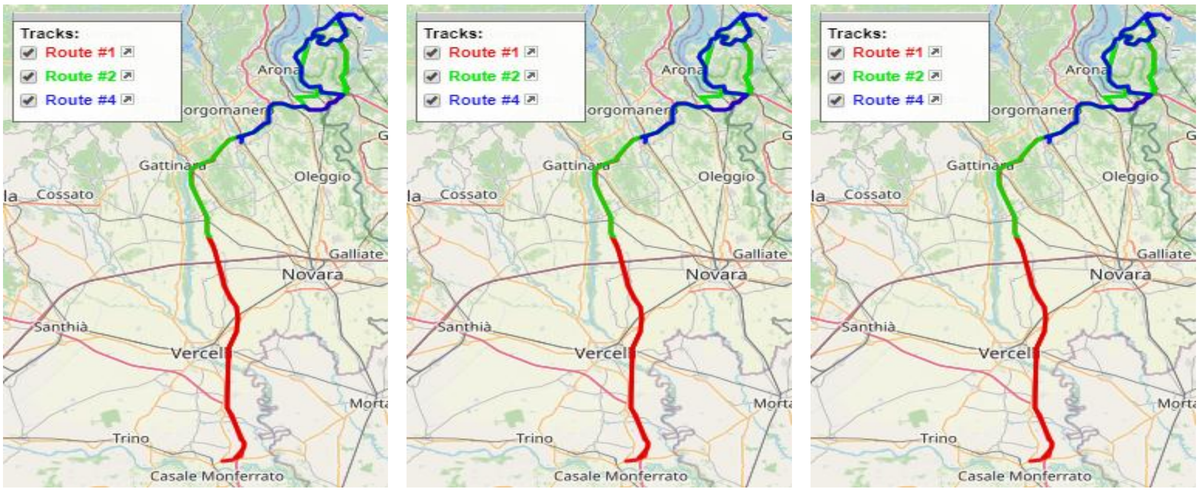
Table 4. Driving phase distributions and statistics of on-road tests

Parameter	Unit	Vehicle #1		Vehicle #2		Vehicle #3		Vehicle #4	
		R#1 (n=5)	R#2 (n=3)	R#1 (n=3)	R#2 (n=3)	R#1 (n=3)	R#4 (n=3)	R#1 (n=3)	R#4 (n=3)
Distance	[km]	153	111	151	102	153	65	153	68
Urban Distance Based	[%]	9	34	10	45	6	52	8	58
Rural Distance Based	[%]	12	33	14	17	9	20	15	15
Motorway Distance Based	[%]	79	33	76	37	85	29	76	27
Urban Time Based	[%]	25	53	25	59	15	65	18	73
Rural Time Based	[%]	13	24	16	14	11	15	16	11
Motorway Time Based	[%]	57	15	56	21	70	15	59	14
Idling Time Based	[%]	5	9	4	7	4	4	7	3

Source: JRC, 2020

Vehicles #3 and #4 belong to the category "other Heavy and Medium Lorries" according to the classification provided in Table 1. Route #1 was designed to fulfil (EU) 2019/318 and applies to all vehicles including Vehicles #3 and #4. Route #4 was designed to fulfil the "minimum" (or slow) targets specification and included high shares of urban and rural driving. More specifically, the provision of ~50% urban, ~25% rural and <10% motorway shares (distance based) with standstill phase not exceeding 10% (time based) was applied. ***Route #5 was supposed to follow the "maximum" targets specification but was not executed as it has similar specifications to Route #1.*** Eventually, Route #1 of a total distance of approximately 150 km as well as a more transient Route #4 of about 65 km were applied for Vehicles #3 and #4. Figure 2 shows the mean speed profile of Vehicles #3 and #4 for the different repetitions over the described routes. Different shares of urban, rural and motorway can be observed for different vehicles over the same route. This can be attributed to a different power-to-weight ratio, resulting in different acceleration behaviour.

Figure 3. Different routes executed with the four vehicles



Source: JRC, 2020

2.3 Instrumentation and Test Protocol

According to draft Annex Xa, the direct torque at all driven axles shall be measured by means of hub torque meters or rim torque meters or half-shaft torque meters. The calibrated range of the selected torque meters shall be at least 10 000 Nm, while the measurement range shall cover the entire range of torque occurring during the VTP test. Each vehicle featured a different torque measurement device with different specifications and characteristics (Table 2). The torquemeters were zeroed after the pre-conditioning phase and before each FC test. This was done with the driven wheels lifted for Vehicles #1, #2 and #4, and by performing a coast-down for Vehicle #3. The drift of the torque was measured directly after the FC measurement by repeating the zeroing procedure and a linear correction was applied to the measured torque signal. The maximum drift of the torque measurement system did not exceed 150 Nm in any of the conducted tests in accordance to the specification provided in the draft Annex Xa.

Based on the draft Annex Xa, the FC of a given VTP test shall be measured on-board with a Fuel Flow Meter (FFM). The device shall measure either the fuel mass or the fuel volume and report the total FC in kilograms or litres, respectively. When the fuel volume is recorded, the values shall be corrected for the thermal expansion of the fuel. The fuel measurement system shall meet certain general requirements described in the draft Annex Xa. In all cases, commercially available FFM devices, measuring the fuel volume and temperature, were provided by the OEMs. The total FC in kilograms per test was calculated by JRC based on the equations provided in the draft Annex Xa. All FFM devices were calibrated in-house from the OEMs before the delivery of the vehicles.

CO_2 and gaseous pollutant emissions (NO_x and CO) were measured by means of PEMS equipment (MOVE, AVL). The PEMS instrumentation followed the provisions described in the ISC regulation (Appendices 1 to 4 to Annex II of Regulation (EU) 582/2011 except for any of the provisions defining the test start and trip). The PEMS was connected to an Exhaust Flow Meter (EFM), while attention was given to leave enough tube diameters length (>four diameters) before and after the EFM to ensure their proper operation, and additionally, not to cause any significant pressure drop by reducing the tailpipe inner diameter. Different EFMs were applied for Vehicles #1 and #2 compared to Vehicles #3 and #4, due to the difference in tailpipe diameter. The zero and span calibration of the analyzers was conducted before each test and the zero and span drift of the PEMS was checked after each test. The recording of PEMS data started during the warm-up phase but the evaluation was based on data recorded during the actual FC measurement. The data analysis was conducted considering the average positive engine work for the entire trip (total emissions [g] / total positive engine work [kWh]) over the VTP relevant test time. More details regarding the PEMS system are provided elsewhere [12].

The daily testing protocol was adapted to follow the specifications described in draft Annex Xa. The fuel tank was almost full at the beginning of the warm-up phase, and the subsequent FC measurement run. The payload for all vehicles was set to approximately 60% of their maximum payload (Table 2). The test mass (actual mass with payload) was calculated by adding, apart from the equipment mass, four persons (~300 kg) in case of the tests conducted with the Coaches and two persons (~150 kg) in case of the Medium Lorries. The tyre inflation pressure was regulated according to the recommendations of the manufacturers. The air conditioning system was switched off in all FC tests, while venting of the cabin was set to the minimum mass flow to minimize auxiliaries' energy consumption. All tests that involved particle filter regeneration were considered invalid and were discarded for the PP1. Before the actual FC measurement tests, the vehicles were warmed up by driving for at least 45 minutes at high load conditions. In some cases, the effectiveness of the warm-up phase was checked by measuring the axle temperature. Results are discussed later in the document. All tests were conducted at dry road conditions, while the average ambient temperature ranged between 5-30°C as specified in the draft Annex Xa. Additional tests were conducted with Vehicle #3 with an increased payload of 80% and with the Engine Start Stop (ESS) disabled. Results of these tests are analyzed in the current report only with regards to the increased payload.

All measurement signals were logged at a sampling frequency of at least 2Hz. Higher sampling frequency data were downsampled to 2Hz. The PEMS data was logged separately at a 1Hz sampling frequency and upsampled during post-processing to 2 Hz. The different data sets were synchronized based on a common signal (e.g. vehicle speed in most cases). Table 5 provides a summary of various elements applied during testing for all vehicles as well as various exceptions applied for different vehicles.

Table 5. *Summary of various elements applied during testing for all vehicles*

Parameter	Excerpt from Annex Xa	Notes
Vehicle Payload	For Heavy Lorries of groups 1 to 3, Medium Lorries and for Buses the payload shall be in the range of 40% to 60% of the max payload	All vehicles were tested at 60% of their maximum payload. Vehicle #3 was also tested at 80% of its maximum payload
Tyre Inflation Pressure	The tyre inflation pressure shall be in line with the recommendation of the manufacturer	Tyre inflation pressure was regulated in line with the recommendation of the manufacturer
Settings for Auxiliaries	All settings influencing the auxiliary energy demand shall be set to minimum reasonable energy consumption. The AC shall be switched off and venting of the cabin shall be set lower than medium mass flow. Cooling and venting for other parts of the vehicle shall be deactivated. For buses door opening and kneeling at stops is not allowed	In vehicles #3 and #4 all auxiliaries were completely switched off during the tests. In Vehicles, #1 and #2 venting in the cabin was regulated to a minimum. No door opening or kneeling was applied
Particle Filter Regeneration	Particle filter regeneration may be initiated and shall be achieved before the VTP. If an initiated particle filter regeneration cannot be achieved before the VTP, the test is invalid and shall be repeated	All tests where particle filter regeneration occurred were not considered for the FC analysis
Route Selection	The route selected for the verification test shall fulfil the requirements set out in Table 3 (Annex Xa)	Different routes applied for different types of vehicles. For details see the previous section
Vehicle Warm-up	Before the fuel consumption measurement starts, the vehicle shall be driven for warm-up *at least for 60 min at a minimum speed of 70 km/h*	For practical reasons, *a 45 min warm-up at high speed* was applied. The axle temperature of Vehicle #1 was checked for confirming the warm-up status
Zeroing – Drift of TMS	The drift shall be measured by zeroing the torque measurement system after the warm-up phase by lifting the axle and measuring the torque at lifted axle directly after the verification test again	Drift was measured according to the provisions for Vehicles #1, #2 and #4. The wheel force sensors of Vehicle #3 were zeroed with a coast down and *no drift correction was applied,* following the supplier's recommendations
Boundary Conditions	The following boundary conditions are prescribed: ○ Average ambient temperature	The following boundary conditions applied: ○ Fulfilled for all vehicles

	between 5-30°C o Road condition 100% dry (no snow or ice allowed) o Route sea level ranging between 0 m to 800 m o Duration of continuous idling at stand-still of maximum 3 min	o Road dry for all tests with Vehicles #1, #2 & #4. *Light rain for some tests with Vehicle #3* o Fulfilled for all vehicles o Fulfilled for all vehicles

Source: JRC, 2020

2.4 Vehicle Simulator

The tests are simulated with VECTO to determine the FC and CO_2 emissions. In VECTO the vehicle's longitudinal vehicle dynamics are simulated over a driving cycle based on the vehicle's technical properties and a driver model. The instantaneous ICE power is determined from the power demand at the wheels, the losses in each component of the powertrain and the auxiliary power demand. The ICE speed is determined from the engaged gear, the powertrain gear ratios and the dynamic tire radius. The ICE torque and speed are used to interpolate from the ICE's fuel map to calculate the instantaneous fuel consumption.

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);
- The driving model considers real-life driving behaviour (e.g. acceleration and braking curves, gear shifting, coasting);
- Input and output via text-files;
- Implemented as Visual Basic. NET application (Windows);
- The graphical user interface for calculation control and editing of the primary input files;
- Declaration mode with locked-values and cryptographic hashing of results for certification purposes

The simulation-core is summarized schematically in Figure 4. A series of studies have shown that VECTO performs adequately and in a similar way as other established commercial or regulation oriented simulators.

In addition to the predefined distance-speed cycles for the certification process, VECTO is also able to simulate the vehicle over a measured VTP cycle for the verification test procedure. An overview of the main features of the VTP mode is shown in Table 6.

Table 6. *Overview of the different simulation modes and input data*

Cycle type	Mode	Road loads (C_dA, mass & RRC)	Engine, Gearbox & Axle	Auxiliaries	Input
VTP	Declaration	Not relevant	Certified values	Predefined value & measured fan speed	Time, wheel speed, wheel torque, engine speed, vehicle speed, fan speed

Source: JRC, 2020

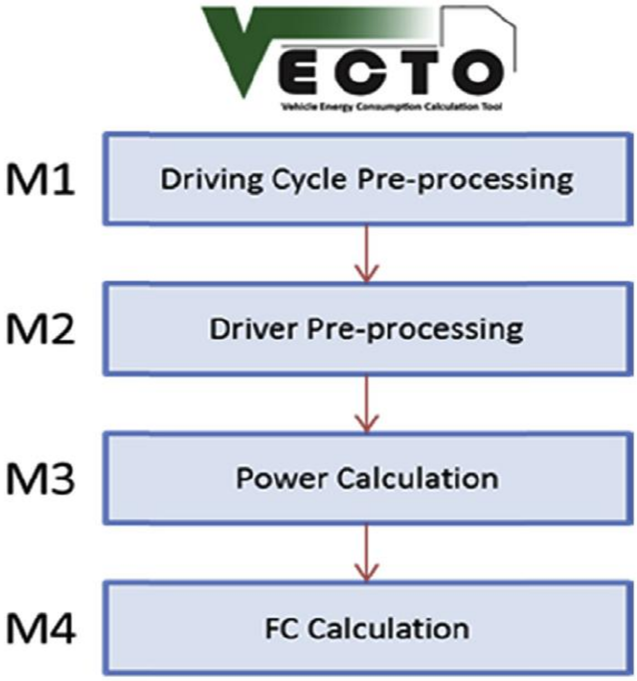
The VTP cycle needs to contain the following measured time signals:

- Time
- Engine speed
- Vehicle speed
- Wheel speed (left and right)
- Wheel torque (left and right)
- Fan speed

- Air compressor status (only for Heavy Buses)

By having the wheel speed and torque as input for VTP simulations, the driver model is bypassed in addition to the parameters that determine the vehicle's road loads (e.g. C_dA, tire RRC and vehicle mass).

Figure 4. VECTO's simulation core



Source: JRC, 2020

The simulations were performed by the respective OEM for Vehicles #1 and #2, with the driving cycle provided by JRC. For Vehicles #3 and #4 the simulations were performed by JRC with the VECTO model provided by the OEM. VECTO development version 0.6.1.1975-DEV was used for all simulations.

3 Results and Discussion

The analysis provided in this section can be separated into three categories based on the targets of the present report. First, a presentation of the FC measurements over the VTP procedure and a subsequent discussion regarding the deviation between measured and VECTO simulated FC values are provided. Practically, in this first section, the feasibility of the VTP procedure for the tested vehicle categories is examined.

The second topic aims in comparing measured CO_2 values from different instruments. FFM FC recorded during the VTP tests are compared with the OBD/ECU readings as well as with the PEMS CO_2 emissions. This analysis is not part of the scope of the PP1 but provides some additional data to the on-going discussion regarding the uncertainty of CO_2 measurement from different sources/instruments.

Finally, a summary of the pollutant emissions over the VTP test is provided. Since the task of evaluating different options to monitor pollutant emissions during the VTP test has been shifted to the HD CO_2 In-Service Verification group, there will be no analysis of the options within the current report.

***Table 7.** Summary of performed tests and simulations*

	HEAVY BUSES										MEDIUM LORRIES									
	Vehicle #1					Vehicle #2					Vehicle #3					Vehicle #4				
	R#1	R#2	R#3	R#4	R#5	R#1	R#2	R#3	R#4	R#5	R#1	R#2	R#3	R#4	R#5	R#1	R#2	R#3	R#4	R#5
FFM FC	√	√	X	N/A	N/A	√	√	X	N/A	N/A	√	N/A	N/A	√	X	√	N/A	N/A	√	X
PEMS CO_2	√	√	X	N/A	N/A	√	√	X	N/A	N/A	√	N/A	N/A	√	X	√	N/A	N/A	√	X
CAN/OBD CO_2	√	√	X	N/A	N/A	√	√	X	N/A	N/A	√	N/A	N/A	√	X	√	N/A	N/A	√	X
VECTO VTP-Mode	√	√	X	N/A	N/A	√	√	X	N/A	N/A	√	N/A	N/A	√	X	√	N/A	N/A	√	X
Pollutant Emissions	√	√	X	N/A	N/A	√	√	X	N/A	N/A	√	N/A	N/A	√	X	√	N/A	N/A	√	X

Source: JRC, 2020

Table 7 provides an overview of the conducted measurements and simulations. N/A refers to routes "Not Applicable" to a given vehicle category for the VTP exercise as described in section 2.2. X refers to tests not performed due to overlapping shares of the different routes. More details regarding the routes are provided in section 2.2.

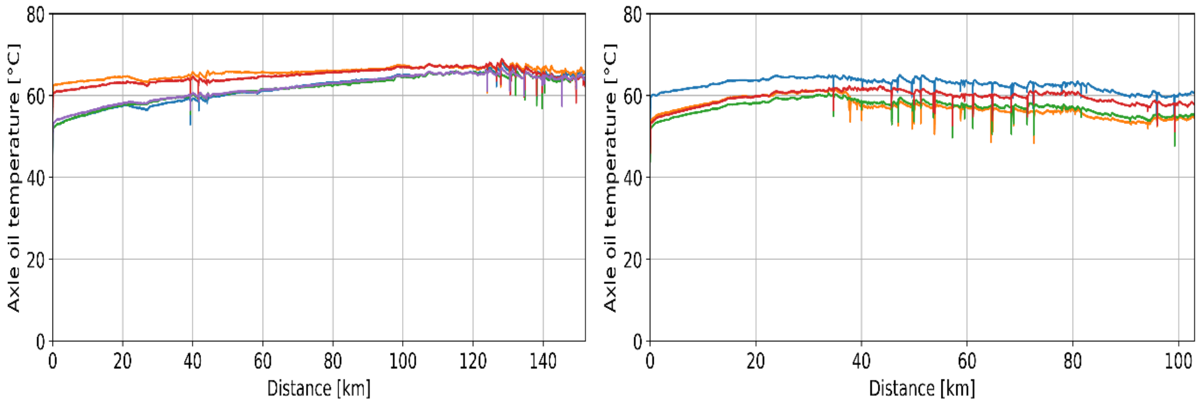
3.1 VTP procedure and FC simulations

The main scope of the current exercise is to investigate the feasibility of the VTP procedure for the tested vehicle categories (Heavy Buses – especially Coaches – and Medium Lorries). This includes the application of the proposed VTP protocol to contribute to the finalization of the draft Annex Xa. A very important element is the investigation of the capability of VECTO to simulate FC for these vehicle categories tested with the proposed protocol. For that reason, FFM measured FC was compared against VECTO simulations under non-strictly controlled environmental and operating conditions of on-road tests. Finally, on-road tests were checked regarding their repeatability, and the routes regarding their suitability, for these vehicle categories. The results are presented in this chapter for each vehicle separately as it is not in the scope of the exercise to compare the vehicles' performance.

3.1.1 Vehicle #1

Five on-road tests were performed over Route #1 and three tests over Route #2. Measurements were conducted following the specifications described in 2.3. The actual FC measurements were initiated after a warm-up phase of approximately 50 min at medium-high load conditions. Unfortunately, it was not possible to perform a warm-up phase of 1h – as prescribed in the draft Annex Xa – due to practical reasons. In any case, the applied warm-up phase proved enough for the engine and drivetrain components to reach acceptable operating temperature. More specifically, the oil temperature of the engine, transmission, and axle after the warm-up were at the level of 97±2°C, 69±3°C and 55±4°C, respectively. Figure 5 depicts the axle temperature evolution during the actual VTP tests measured with a dedicated thermocouple installed by the OEM. The average temperature over the entire cycle is 63°C for the motorway cycle and 58°C for the urban cycle, taking into account all repetitions. In general, the temperature seems to increase during motorway driving and slightly decrease again during urban/rural driving. Afternoon tests ran under slightly higher temperature compared to morning tests, following the ambient temperature conditions. Based on the evidence extracted from Figure 5 it is concluded that applied warm-up was sufficient for a VTP test. Tests were performed at ambient conditions with an average temperature of 18±2°C and relative humidity of 76±11%.

Figure 5. Axle temperature during VTP tests on Route #1 (left) and Route #2 (right)



Source: JRC, 2020

Table 8 gives an overview of some key test results for Vehicle #1 over Route #1 which fulfils the specifications described in 2019/318. Measured and simulated WSFC values are normalized to the average measured WSFC value of both routes. The deviation [%] is defined as the difference between the simulated and measured WSFC divided by the measured WSFC. The deviation for each test was calculated for comparison purposes against previous campaigns conducted with HDVs under similar testing conditions. *Finally, the VTP ratio (C_{VTP}) is calculated according to the equation provided in 7.3 of the draft Annex Xa.* For a test to be considered successful, the C_{VTP} value should not exceed 1.075.

Route #1 tests exhibit a very good agreement between measured and simulated WSFC values. More specifically, the deviation was constantly about 3% in all repetitions. These values are better than those reported in previous campaigns for another Heavy Bus [11] and similar to other types of HDVs tested under similar conditions [10]. More specifically, Grigoratos et al. (2018) reported a deviation of approximately 8-10% between the FFM based WSFC and VECTO simulated values for a Euro VI Coach tested over – VTP-like – conditions. Further development of VECTO might be a reason for the improvement compared to the 2018 campaign. On the other hand, Grigoratos et al. [10] reported deviations of 3-5% (PEMS CO_2 vs. VECTO P_{wheel} mode and PEMS CO_2 vs. VECTO Engineering Mode) for three Euro VI Heavy Lorries tested on-road over a similar protocol to that of the current exercise. It seems that VECTO performs accurately for this specific vehicle under the proposed Route #1. This is confirmed by the C_{VTP} value, which did not exceed 1.035 and fulfilled the pass criterion defined for Heavy Lorries in (EU) 2019/318.

Table 8. Test values for Vehicle #1 over Route #1

	Test	Average speed [km/h]	W_{Wheel} [kWh]	WSFC FFM [-]	WSFC VECTO [-]	Deviation [%]	C_{VTP} [-]
Route #1	#1	69.9	102.9	0.994	0.964	-3.0	1.031
	#2	71.7	101.8	0.991	0.961	-3.0	1.031
	#3	71.1	103.2	0.987	0.963	-2.5	1.026
	#4	66.5	102.9	0.995	0.968	-2.8	1.029
	#5	71.7	101.5	0.996	0.964	-3.2	1.033
Average	**-**	**70.2**	**102.5**	**0.993**	**0.964**	**-2.9**	**1.030**

Source: JRC, 2020

Table 9 gives an overview of the test results for Vehicle #1 over Route #2. Tests on Route #2 demonstrate an acceptable agreement between the measured and simulated WSFC. The deviation was approximately 5% in all tests. These values are worse than those reported for Route #1. The difference can be attributed to the higher transient share of Route #2 compared to Route #1 as described in Table 4. It seems that VECTO does not perform equally well under highly transient conditions associated with urban (and rural) driving – including a high share of start-stop and idling – compared to more constant motorway conditions. However, the C_{VTP} also, in this case, did not exceed 1.075 and fulfilled the pass criterion defined for Heavy Lorries in (EU) 2019/318.

Table 9. Test values for Vehicle #1 over Route #2

	Test	Average speed [km/h]	W_{Wheel} [kWh]	WSFC FFM [-]	WSFC VECTO [-]	Deviation [%]	C_{VTP} [-]
Route #2	#1	42.7	85.4	1.015	0.961	-5.3	1.056
	#2	43.4	86.2	1.014	0.965	-4.8	1.051
	#3	45.3	84.6	1.008	0.957	-5.1	1.053
Average	**-**	**43.8**	**85.4**	**1.012**	**0.961**	**-5.1**	**1.053**

Source: JRC, 2020

The on-road tests were checked regarding their repeatability to understand the suitability of the proposed routes for the individual vehicle categories. For each route, the standard error (SE) over the different tests is listed in Table 10.

Table 10. SE of test parameters for Vehicle #1

	Average speed [%]	W_{Wheel} [%]	FC FFM [%]	FC PEMS [%]	FC ECU [%]	WSFC FFM [%]	WSFC PEMS [%]	WSFC ECU [%]	$C_{\_VTP}$ [%]
Route #1	3.1	0.8	0.7	0.9	1.0	0.4	0.5	0.3	0.3
Route #2	2.1	1.0	1.4	1.3	1.4	0.4	0.3	0.4	0.3

Source: JRC, 2020

The SE is the ratio of the standard deviation divided by the average value of the conducted tests. In general, Vehicle #1 exhibits high repeatability on both on-road tests. In all cases, the SE for the FC and WSFC did not exceed 1%, regardless of the measurement instrument (FFM, PEMS, ECU). These values are lower than the ones reported in previous studies for other Euro VI HDVs [10-11]. A slightly larger SE is observed for the WSFC over Route #2, which can be attributed to its more transient nature compared to Route #1. Overall, and taking into account VECTO performance, Route #1, or a similar one, seems more appropriate for this vehicle category.

3.1.2 Vehicle #2

Three on-road tests were performed on Route #1 and a shortened version of Route #2, respectively, according to the specifications described in 2.3. FC measurements were initiated after a warm-up phase of approximately 45 min at medium-high load conditions. Unfortunately, it was not possible to perform a warm-up phase of 1h as prescribed in the draft Annex Xa due to practical reasons. Previous experience from similar vehicles shows that a 45 min warm-up phase is adequate. Tests were performed at ambient conditions with an average temperature of 14±2°C and relative humidity of 34±15%.

Table 11 provides an overview of the test results for Vehicle #2 over Route #1. The measured and simulated WSFC values are normalized with respect to the average measured WSFC value (FFM) for both routes. Tests over Route #1 show a very good agreement between the measured and simulated WSFC values. The deviation is approximately 3% as in the case of Vehicle #1, except for one test which demonstrated a deviation of 4.6%. These values are better than previously reported for a Coach tested under similar protocol [11] and similar to values reported for other types of HDVs [10]. It is confirmed that VECTO performs accurately for this type of vehicles tested under the proposed Route #1. This remark is strengthened by the C_{VTP} value, which for Route #1 did not exceed 1.050 and fulfilled the pass criterion defined in (EU) 2019/318 for Heavy Lorries.

Table 11. *Test values for Vehicle #2 over Route #1*

	Test	Average speed [km/h]	W_{Wheel} [kWh]	WSFC FFM [-]	WSFC VECTO [-]	Deviation [%]	C_{VTP} [-]
Route #1	#1	71.2	121.8	0.975	0.931	-4.6	1.048
	#2	69.3	118.9	0.970	0.937	-3.4	1.035
	#3	71.7	118.5	0.963	0.933	-3.1	1.032
Average	**-**	**70.7**	**119.7**	**0.969**	**0.934**	**-3.7**	**1.038**

Source: JRC, 2020

Table 12 illustrates the test results for Vehicle #2 over Route #2. Route #2 tests demonstrate similar or slightly better agreement between the measured and simulated WSFC values compared to Route #1 tests. The deviation was approximately 3% in all tests. Likewise, the C_{VTP} in the current exercise did not exceed 1.035 and fulfilled the pass criterion defined in (EU) 2019/318 for vehicle categories 4, 5, 9 and 10. In this case, VECTO seems to be able to successfully simulate Vehicle #2 under different driving conditions and without being affected by higher transient conditions of urban and rural driving. This contradicts the findings from Vehicle #1. However, the differences are not significant.

Table 12. *Test values for Vehicle #2 over Route #2*

	Test	Average speed [km/h]	W_{Wheel} [kWh]	WSFC FFM [-]	WSFC VECTO [-]	Deviation [%]	C_{VTP} [-]
Route #2	#1	48.1	78.7	1.035	1.000	-3.4	1.035
	#2	49.8	83.8	1.015	0.988	-2.7	1.027
	#3	48.4	76.8	1.042	1.011	-3.0	1.031
Average	**-**	**48.8**	**79.8**	**1.031**	**1.000**	**-3.0**	**1.031**

Source: JRC, 2020

Also, in this case, the on-road tests were checked regarding their repeatability with the aim of understanding the suitability of the proposed routes for Coaches. For each route, the standard error (SE) over the different tests is listed in Table 10.

Table 13. SE of test parameters for vehicle #2

	Average speed [%]	W_{Wheel} [%]	FC FFM [%]	FC PEMS [%]	FC ECU [%]	WSFC FFM [%]	WSFC PEMS [%]	WSFC ECU [%]	$C_{\_VTP}$ [%]
Route #1	1.8	1.5	2.0	2.3	1.7	0.6	0.8	1.3	0.8
Route #2	1.8	4.5	3.1	3.1	3.4	1.4	1.5	1.4	0.4

Source: JRC, 2020

The SE for the FC and WSFC did not exceed 3.5% (FFM, PEMS, ECU). These values are slightly higher than the ones from Vehicle #1; however, the difference is not significant. For both vehicles, a larger SE is observed for the WSFC over Route #2, which can be attributed to its more transient nature compared to Route #1. Overall, Route #1, or a similar one, seems more appropriate for the VTP of Heavy Buses and more particularly for Coaches.

3.1.3 Vehicle #3

Vehicle #3 belongs to Medium Lorries (N2 exceeding 5 tons and not exceeding 7.4 tons maximum mass with engine type approval according to Regulation (EU) 595/2009). Three on-road tests were performed on Route #1 and three tests on a shortened version of Route #4. FC measurements were initiated after a warm-up phase of approximately 45 min at medium-high load conditions. Tests were performed at ambient conditions with an average temperature of 9±2°C and relative humidity of 86±5%. The periods where ESS was active (i.e. the engine was not running) were removed from the cycle in a post-processing step because VECTO does not simulate the engine switching off.

Table 14 gives an overview of some key test results drawn on Route #1. No good agreement between the measured and simulated WSFC values is observed. The deviation is approximately 13% in all repetitions, with VECTO systematically overestimating FC. There are two reasons explaining the observed discrepancy. Firstly, the generic values in VECTO significantly overestimate the electrical power demand of auxiliaries for medium lorries compared to the actual electrical power demand during the VTP test. More specifically, VECTO ran the simulations with average electrical power of approximately 1kW, whereas the actual electrical power of Vehicle #3 is not expected to exceed 0.35kW during a VTP test. This difference introduces an error in the range of approximately 5-6%. Additionally, VECTO simulations were performed with non accurate component input data. More specifically, the engine fuel consumption map and the gearbox loss map were not measured as specified in the regulation and thus it is expected to introduce a significant error in the simulations. Unfortunately, this error could not be quantified with the available data. In all cases, the C_{VTP} value was always lower than 1.000 and fulfilled the pass criterion defined for Heavy Lorries in (EU) 2019/318.

Table 14. Test values for Vehicle #3 over Route #1

	Test	Average speed [km/h]	W_{Wheel} [kWh]	WSFC FFM [-]	WSFC VECTO [-]	Deviation [%]	C_{VTP} [-]
Route #1	#1	70.9	46.2	0.983	1.103	12.3	0.891
	#2	73.5	48.8	0.967	1.093	13.0	0.885
	#3	70.5	45.8	0.983	1.108	12.7	0.887
Average	**-**	**71.6**	**47.0**	**0.978**	**1.101**	**12.7**	**0.888**

Source: JRC, 2020

Table 15 provides some key results gained on Route #4. Again, no agreement between the measured and simulated WSFC values is found. The deviation is even higher compared to Route #1 and reaches up to 15% in all repetitions following the issues described in the previous paragraph. The C_{VTP} value was always lower than 1.000 and fulfilled the pass criterion defined for Heavy Lorries in (EU)

2019/318. Another objective of the current exercise was to investigate – where possible – the influence of the application of different payloads to the VTP performance. In case of Vehicle #3 it was possible to apply two different payloads on Route #4. Apart from the default 60%, a payload of 80% was applied for three repetitions. Table 15 shows no significant differences with the application of an increased payload.

Table 15. *Test values for Vehicle #3 over Route #4*

	Test	Average speed [km/h]	W_{Wheel} [kWh]	WSFC FFM [-]	WSFC VECTO [-]	Deviation [%]	C_{VTP} [-]
Route #4	#1	47.2	17.9	1.027	1.179	14.8	0.871
	#2	47.3	18.5	1.016	1.171	15.2	0.868
	#3	47.3	18.0	1.024	1.183	15.4	0.866
Average	**-**	**47.3**	**18.1**	**1.022**	**1.178**	**15.1**	**0.868**
Route #4[1]	#1	46.3	19.1	1.010	1.162	15.0	0.869
	#2	46.0	19.4	1.009	1.158	14.8	0.871
	#3	46.7	19.4	1.009	1.159	14.9	0.870
Average	**-**	**46.3**	**19.3**	**1.009**	**1.160**	**14.9**	**0.870**

([1])Repetitions applied with 80% payload

Source: JRC, 2020

The standard error (SE) of the different tests for Vehicle #3 is listed in Table 16. Vehicle #3 exhibits a high repeatability on all on-road tests. The SE for the FC and WSFC did not exceed 3%, regardless the measurement instrument (FFM, PEMS, ECU). These values are close to the ones reported for Heavy Buses in the current study. A slightly larger SE is observed for the FC and WSFC over Route #1, despite the less transient conditions. It seems that Route #4, or a generally more transient cycle compared to the regulated Route #1, is more appropriate for this vehicle category. Regarding the influence of the payload, although the SE of the wheel work and FC are generally lower for the tests with 80% payload, the SE of the VSFC is similar. Hence, it seems that a higher payload is not required to increase the repeatability of the procedure.

Table 16. *SE of test parameters for Vehicle #3*

	Average speed [%]	W_{Wheel} [%]	FC FFM [%]	FC PEMS [%]	FC ECU [%]	WSFC FFM [%]	WSFC PEMS [%]	WSFC ECU [%]	C_{VTP} [%]
Route #1	2.3	3.5	2.6	2.5	2.7	0.9	1.0	0.7	0.3
Route #4	0.1	1.8	1.3	1.9	1.7	0.5	0.1	0.2	0.3
Route #4[1]	0.8	0.9	0.8	0.7	0.8	0.1	0.4	0.1	0.1

([1])Repetitions applied with 80% payload

Source: JRC, 2020

3.1.4 Vehicle #4

Three on-road tests were performed on Route #1 and Route #4, respectively, according to the specifications described in 2.3. The measurements were started after a warm-up of the vehicle at medium-high load conditions for at least 45 min. Tests were performed over ambient conditions with an average temperature of 10±4°C and a relative humidity of 49±33%. Table 17 gives an overview of some key test results on Route #1.

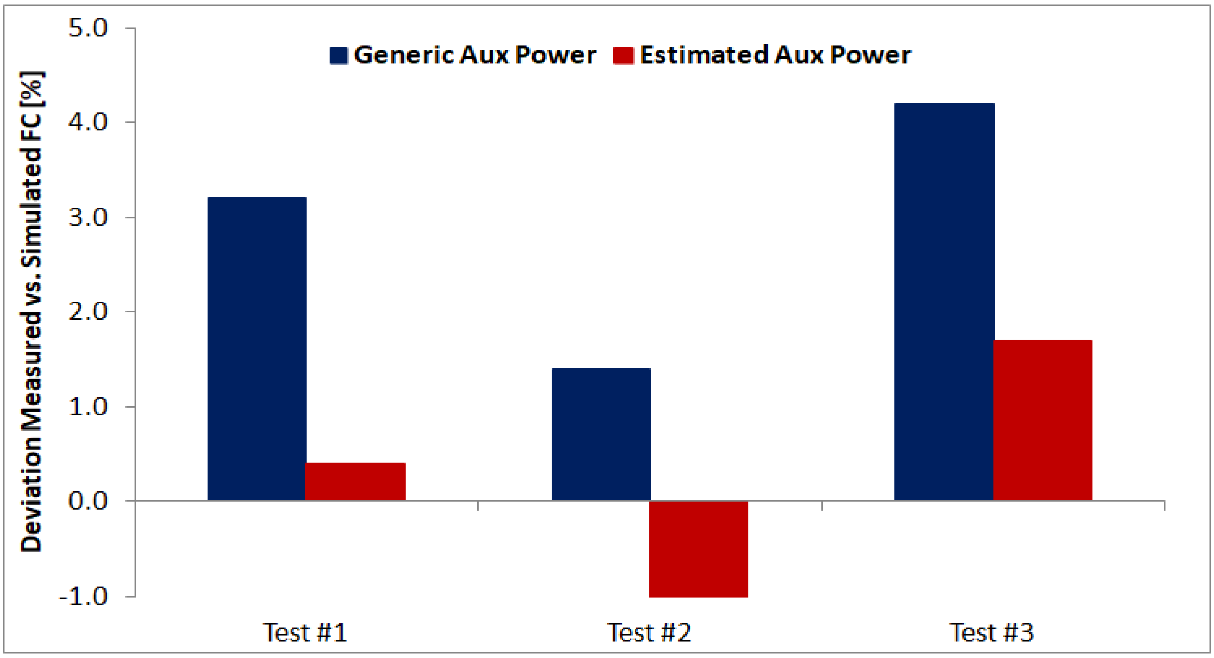
Table 17. *Test values for Vehicle #4 over Route #1*

	Test	Average speed [km/h]	W_{Wheel} [kWh]	WSFC FFM [-]	WSFC VECTO [-]	Deviation [%]	C_{VTP} [-]
Route #1	#1	66.0	61.4	0.961	0.992	3.2	0.969
	#2	67.1	66.4	0.963	0.977	1.4	0.986
	#3	67.4	66.2	0.935	0.975	4.2	0.959
Average	**-**	**66.9**	**64.7**	**0.953**	**0.981**	**2.9**	**0.971**

Source: JRC, 2020

The measured and simulated WSFC values are normalized to the average measured value of Vehicle #4 for both routes. Route #1 tests exhibit a good agreement between the measured and simulated WSFC values. In one case the deviation reached 4.2%, while the other two tests were more accurately simulated by VECTO. In all cases, the simulated WSFC appears to be higher than the measured WSFC meaning that VECTO constantly overestimates the FC of this vehicle. This is due to the overestimation of the auxiliaries' power in VECTO for Medium Lorries. More specifically, VECTO ran the simulations with average electrical power of approximately 1kW, whereas the actual electrical power of Vehicle #4 was found to be lower than 0.4kW. A comparison of the simulation deviations observed with an adjusted auxiliary power based on the average measured electrical power against the generic values is depicted in Figure 6. The average simulation error is significantly reduced by applying a lower generic power demand for the electrical system.

Figure 6. Deviation measured vs. simulated FC for Vehicle #4 on Route #1 with different auxiliary considerations



Source: JRC, 2020

The C_{VTP} in the current exercise did not exceed 1.000 and fulfilled the pass criterion defined in (EU) 2019/318 for vehicle categories 4, 5, 9 and 10. No previous data for similar vehicles are available; therefore, it is not easy to generalize the conclusions drawn for this vehicle to the broader category. On the other hand, the proposed Route seems to be acceptable for this vehicle category.

Table 18 gives an overview of some key test results on Route #4. These tests are successfully simulated in VECTO; however, the deviations are somewhat higher than the ones observed in Route #1. The difference can be attributed to the higher transient share of Route #4 compared to Route #1. Once more with this vehicle VECTO overestimates the FC due to overestimation of the auxiliaries' power in VTP Mode. The C_{VTP} did not exceed 1.000 and fulfilled the pass criterion defined in (EU) 2019/318 for Heavy Lorries. No previous data for similar vehicles are available; therefore, it is not easy to understand if VECTO performs satisfactorily with this vehicle.

Table 18. *Test values for Vehicle #4 over Route #4*

	Test	Average speed [km/h]	W_{Wheel} [kWh]	WSFC FFM [-]	WSFC VECTO [-]	Deviation [%]	C_{VTP} [-]
Route #4	#1	45.3	23.3	1.038	1.083	4.3	0.958
	#2	45.2	23.0	1.066	1.080	1.3	0.987
	#3	44.3	22.8	1.036	1.093	5.5	0.948
Average	**-**	**44.9**	**23.0**	**1.047**	**1.085**	**3.7**	**0.964**

Source: JRC, 2020

On-road tests were checked regarding their repeatability and the standard error (SE) over the different tests is listed in Table 19. PEMS data refer to two tests instead of three because there was a malfunction of the PEMS system during one repetition of Route #1.

Table 19. *SE of test parameters for Vehicle #4*

	Average speed [%]	W_{Wheel} [%]	FC FFM [%]	FC PEMS [%]	FC ECU [%]	WSFC FFM [%]	WSFC PEMS [%]	WSFC ECU [%]	C_{VTP} [%]
Route #1	1.1	4.4	4.1	3.9	3.4	1.7	1.5	2.0	1.4
Route #4	1.3	1.0	1.9	0.9	1.2	1.6	0.3	0.6	2.1

Source: JRC, 2020

Vehicle #4 exhibits generally a good repeatability on all on-road tests. The SE for the FC and WSFC did not exceed 5%, regardless of the measurement instrument (FFM, PEMS, ECU). In agreement with the findings for Vehicle #3, a generally higher SE is observed for the FC and WSFC over Route #1 despite the higher transient conditions of Route #4. Also in this case, it seems that Route #4, or a generally more transient cycle compared to the regulated Route #1, is more appropriate for this vehicle category to achieve repeatable on-road tests.

3.2 FC and CO_2 measurements

The scope of the current chapter is to provide a thorough presentation of the FC data measured by means of different instruments. The main objective is to understand the deviation between measured FC values between PEMS and FFM and contribute to the on-going discussion regarding the feasibility of PEMS instrumentation to provide accurate FC measurements. At the same time, ECU FC is studied and compared to FFM FC to understand how accurately it performs. The FFM FC is used as a benchmark. The results are presented in this chapter for each vehicle separately as it is not in the scope of the exercise to compare the vehicles' performance.

3.2.1 Vehicle #1

Table 20 presents an overview of the normalized WSFC values measured with different methods as well as the deviations from the reference instrument (FFM). The FC calculated from the PEMS CO_2 emissions is very close to the corresponding FFM FC. For both routes, the PEMS FC is consistently higher than the FFM FC; however, the deviation does not exceed 2% and falls within the experimental uncertainty. It is noted that there are no significant differences in the deviations among the two routes. Practically, PEMS performs equally well both under non-transient and highly transient conditions.

Table 20. Overview of WSFC values from different instruments for Vehicle #1

	Test	WSFC FFM [-]	WSFC PEMS [-]	WSFC ECU [-]	Deviation FFM-PEMS [%]	Deviation FFM-ECU [%]
Route #1	#1	0.994	1.001	1.014	0.7	2.0
	#2	0.991	0.996	1.006	0.5	1.6
	#3	0.987	1.005	1.012	1.8	2.5
	#4	0.995	1.006	1.013	1.1	1.7
	#5	0.996	1.008	1.011	1.2	1.6
Average Route #1	**-**	**0.993**	**1.003**	**1.011**	**1.1**	**1.9**
Route #2	#1	1.015	1.019	1.040	0.4	2.5
	#2	1.014	1.021	1.041	0.7	2.6
	#3	1.008	1.014	1.033	0.7	2.5
Average Route #2	**-**	**1.012**	**1.018**	**1.038**	**0.6**	**2.5**

Source: JRC, 2020

Slightly higher differences are observed when ECU FC values are compared to the reference FFM values. However, the deviations do not exceed 3% and are generally lower (±5%) compared to the values reported elsewhere for seven Euro VI HDVs equipped with FFM and tested under similar conditions [14]. Slightly higher deviations are observed over the Route #2 compared to Route #1; however, the difference falls within the experimental uncertainty. It is noteworthy that for Vehicle #1 both PEMS and ECU overestimate the actual FC regardless the selected route. Overall, it can be concluded that both methods provide a quite accurate measurement of the FC, regardless of the testing conditions.

3.2.2 Vehicle #2

Table 21 shows the normalized WSFC values measured with different methods for Vehicle #2. Additionally, the deviations from the reference instrument are shown. There seems to be satisfactorily agreement between the PEMS and FFM FC. More specifically, the deviation goes up to approximately 4% for Route #1 and 3% for Route #2. These values are generally higher than the ones found for Vehicle #1; however, within acceptable levels according to the authors. Also, in this case, the FC calculated from the PEMS CO_2 is consistently higher compared to the corresponding FFM FC. The PEMS instrument seems to perform slightly better under transient conditions; however, the differences are within the experimental uncertainty.

Table 21. Overview of WSFC values from different instruments for Vehicle #2

	Test	WSFC FFM [-]	WSFC PEMS [-]	WSFC ECU [-]	Deviation FFM-PEMS [%]	Deviation FFM-ECU [%]
Route #1	#1	0.975	1.017	0.928	4.3	-4.8
	#2	0.970	1.008	0.947	3.9	-2.4
	#3	0.963	1.001	0.924	3.9	-4.1
Average Route #1	**-**	**0.969**	**1.009**	**0.933**	**4.0**	**-3.8**
Route #2	#1	1.035	1.068	0.985	3.2	-4.8

	#2	1.015	1.040	0.980	2.5	-3.4
	#3	1.042	1.068	1.006	2.5	-3.4
Average Route #2	**-**	**1.031**	**1.059**	**0.990**	**2.7**	**-3.9**

Source: JRC, 2020

Generally, higher deviations are observed when the ECU FC values are compared to the reference FFM values. In this case, the deviations go up to 5% and are in line with the values reported elsewhere for seven Euro VI HDVs tested under similar conditions [14]. There are no statistically significant differences between the observed deviations among the two routes. While constantly PEMS overestimate the actual FC, the ECU underestimates it over both selected routes.

3.2.3 Vehicle #3

Table 22 presents an overview of the normalized WSFC values measured with different methods as well as the deviations from the reference instrument for Vehicle #3. No PEMS and ECU data are available for test #3 on Route #2 due to technical reasons.

It is observed that the PEMS calculated FC is very close to the corresponding FFM FC. The deviation does not exceed 0.5% on Route #1, while it is slightly higher – up to 1% – on Route #4. There is no statistical difference in the observed deviations, therefore the PEMS seems to perform equally well on both routes. The PEMS calculated FC is slightly lower than the FFM FC, except for one test, in contrast to what has been observed for Vehicles #1 and #2. The difference might be explained by the application of a different exhaust flowmeter compared to Heavy Buses which results in an overall different PEMS setup.

Table 22. *Overview of WSFC values from different instruments for Vehicle #3*

	Test	WSFC FFM [-]	WSFC PEMS [-]	WSFC ECU [-]	Deviation FFM-PEMS [%]	Deviation FFM-ECU [%]
Route #1	#1	0.983	0.982	1.026	-0.1	4.4
	#2	0.967	0.965	1.012	-0.3	4.6
	#3	0.983	0.981	1.024	-0.2	4.2
Average Route #1	**-**	**0.978**	**0.976**	**1.021**	**-0.2**	**4.4**
Route #4	#1	1.027	1.018	1.085	-0.8	5.6
	#2	1.016	1.020	1.082	0.4	6.5
	#3	1.024	*	*	*	*
Average Route #4	**-**	**1.022**	**1.019**	**1.084**	**-0.2**	**6.1**

Source: JRC, 2020

Higher deviations are observed when the ECU FC values are compared to the reference FFM values. Deviations are similar to the values reported for HDVs in the literature [14]. Slightly higher deviations are observed over the more transient Route #4. In this case the PEMS underestimates the actual FC, while the ECU overestimates it, regardless of the selected route. This could be partly attributed to the transient effect of engine start-stop phases, even though these phases were removed for the cycle. It is not known whether the affects the only the FFM or also the ECU reading.

3.2.4 Vehicle #4

Table 23 presents the normalized WSFC values measured with different methods and the deviations from the reference instrument for Vehicle #4. No PEMS and ECU data are available for test #2 on Route #1 and test #3 on Route #4 due to technical issues with the instruments.

Table 23. Overview of WSFC values from different instruments for Vehicle #4

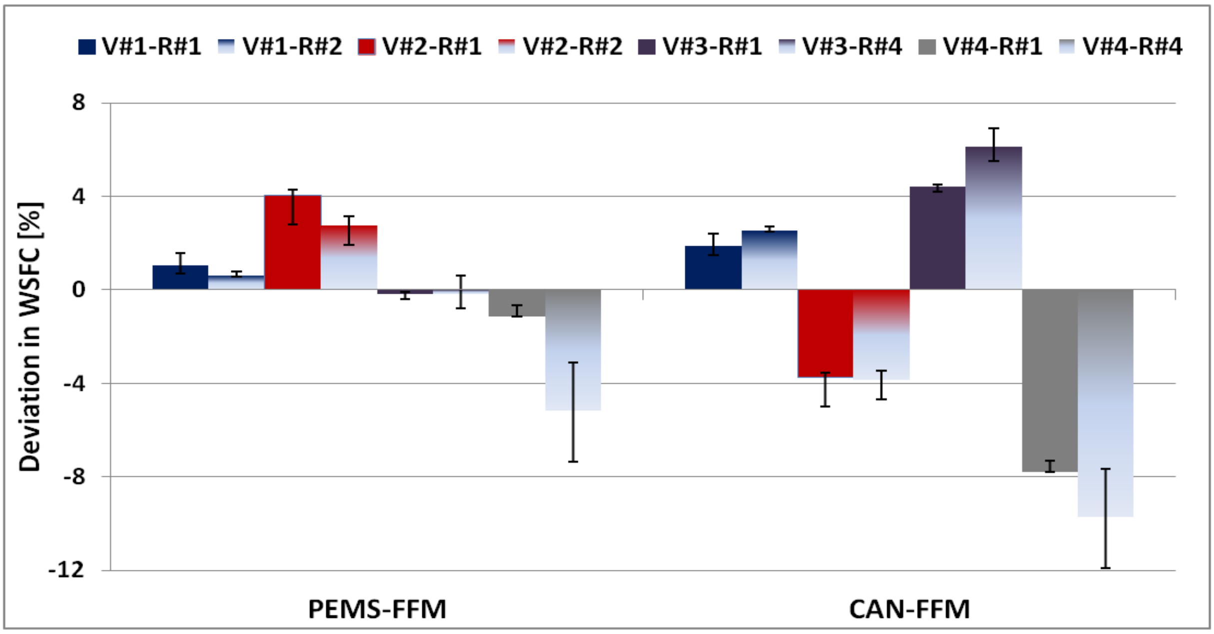
	Test	WSFC FFM [-]	WSFC PEMS [-]	WSFC ECU [-]	Deviation FFM-PEMS [%]	Deviation FFM-ECU [%]
Route #1	#1	0.961	0.947	0.887	-1.5	-7.8
	#2	0.963	*	*	*	*
	#3	0.935	0.928	0.862	-0.8	-7.8
Average Route #1	**-**	**0.953**	**0.938**	**0.874**	**-1.2**	**-7.8**
Route #4	#1	1.038	1.000	0.953	-3.7	-8.2
	#2	1.066	0.996	0.946	-6.6	-11.3
	#3	1.036	*	*	*	*
Average Route #4	**-**	**1.047**	**0.998**	**0.950**	**-5.2**	**-9.7**

Source: JRC, 2020

The PEMS calculated FC is very close to the corresponding FFM WSFC for Route #1. On the other hand, much higher deviations are found on Route #4 and particularly over the second repetition. More specifically, the deviation does not exceed 1.5% for Route #1, while it goes up to almost 7% for test #2 of Route #4. In this case, the PEMS seems to perform much better under less transient conditions unlike the other vehicle of the same category (Vehicle #3). The PEMS FC is consistently lower than the FFM FC, regardless of the selected route. This is similar to Vehicle #3 and opposite to the Heavy Buses. The difference is explained by the modified PEMS setup.

Higher differences are observed when the ECU FC is compared to the reference FFM values. The deviations are close to 8% and in one case exceeded 10%. This could be attributed to the installation of the FFM in the fuel lines, that introduced a pressure drop in the feed line and a higher backpressure in the return line. Similar to PEMS, the ECU constantly underestimates the actual FC over both selected routes.

Figure 7. Averaged deviations of different instruments for all tested vehicles



Source*: JRC, 2020*

Figure 7 visualizes the averaged deviations among the different instruments for all tested vehicles. The error bars correspond to the Standard Deviation (StDev) of the three repetitions (five for Vehicle #1 on Route #1). It is seen that the PEMS generally succeeds in measuring the actual FC for both vehicle categories. In all cases the deviation between the FFM and the PEMS calculated FC is less than 5% with most tests being close or lower than 3%. In the case of Heavy Buses, the PEMS always overestimates the FC, whereas it appears to be more accurate over the more transient Route #2 compared to Route #1. Medium Lorries exhibited slightly higher deviations compared to Heavy Buses. The PEMS constantly underestimates the FC, whereas it appears to be more accurate over the less transient Route #1 compared to Route #4. There is no clear explanation regarding the different behaviour among the two vehicle categories or the different routes. However, it is noteworthy that a different flowmeter was used for PEMS testing with the Medium Lorries compared to the Coaches.

Figure 7 shows that ECU is generally slightly less accurate than PEMS in providing the actual FC, regardless the vehicle category and the selected route. In case of Heavy Buses ECU seems to perform satisfactorily with the deviation being within a ±4%. These values are in line with those reported for HDVs in the literature [14]. In Vehicle #1 ECU overestimates the FC, while in Vehicle #2 the opposite trend is observed. ECU performance does not seem to be affected by the type of route. For Medium Lorries there are two different cases. More specifically, the ECU of Vehicle #3 performs satisfactorily with the deviation being within a ±6%. However, in Vehicle #4 the ECU significantly underestimates the FC at a 8-10% level. ECU performance does not seem to be affected by the type of route.

3.3 Pollutant emissions measurements

An important element of the PP1 – as defined in 2019 – was to evaluate the feasibility of different options to monitor pollutant emissions during the VTP test. The current study aimed to collect experimental data to support a subsequent analysis and the final selection of the methodology to adopt. In the meantime, the task of evaluating different options to monitor pollutant emissions during the VTP test has been decided to be addressed by a different group. Therefore, the current report will only provide collected data on pollutant emissions and will not go into the analysis of possible different options. These will be addressed by the HD CO_2 In-Service Verification group steered by DG-CLIMA. Data for NO_x and CO emissions were collected for all vehicles. The results are presented in this chapter for each vehicle separately as they are not comparable to each other.

3.3.1 Vehicle #1

Table 24 gives an overview of the pollutant emissions recorded during the VTP test for Vehicle #1. Five tests were considered on Route #1 and three on Route #2. All values refer to g/kWh at the engine and were calculated following the specification of the draft Annex Xa. Apart from the NO_x and CO emissions of the individual tests, the average value of the emissions, as well as the standard deviation of the repetitions, is also provided.

The NO_x emissions were generally low and did not exceed 0.1 g/kWh. It is also observed that the emissions were quite repeatable among the different tests. The average NO_x was found to be approximately 0.06-0.07 g/kWh without noticing significant differences among the two routes. These values are on the lower end of the reported range for five Euro VI HDVs tested under similar conditions [15]. It is important to note that the pollutant measurements were conducted under a fully warm operation of the engine and the aftertreatment system, thus it is expected that the catalyst would be fully effective. The experimental results confirm this assumption. Cold start was not considered at all. However, NO_x emissions were far below the EURO VI engine certification limit (0.46 g/kWh). NH_3 emissions have not been considered at all and should be measured in parallel to NO_x emissions to evaluate the operation of the aftertreatment system.

Table 24. *Overview of pollutant emissions during the VTP for Vehicle #1*

	Test	NO_x [g/kWh]	CO [g/kWh]
Route #1	#1	0.101	0.013
	#2	0.044	0.008
	#3	0.065	0.004
	#4	0.042	0.005

	#5	0.087	0.188
Average Route #1	-	**0.068±0.026**	**0.043±0.026**
Route #2	#1	0.051	0.013
	#2	0.082	0.280
	#3	0.057	0.141
Average Route #2	-	**0.063±0.016**	**0.145±0.134**

Source: JRC, 2020

The CO emissions were also low with average values ranging between 0.05-0.15 g/kWh. The values recorded over Route #1 are one order of magnitude lower than the ones reported for five Euro VI HDVs tested under similar conditions [15]. In this case, there seems to be a difference among the routes with the more transient exhibiting higher CO emissions. In any case, CO emissions did not exceed the EURO VI engine certification limit (4.0 g/kWh).

3.3.2 Vehicle #2

Table 25 gives an overview of the pollutant emissions recorded during the VTP test for Vehicle #2. Three tests were considered on both routes. All values refer to g/kWh at the engine and were calculated following the specification of the draft Annex Xa. Apart from the NO_x and CO emissions of the individual tests, the average value of the emissions, as well as the standard deviation of the repetitions, is provided.

Table 25. *Overview of pollutant emissions during the VTP for Vehicle #2*

	Test	NO_x [g/kWh]	CO [g/kWh]
Route #1	#1	0.162	0.289
	#2	0.175	0.001
	#3	0.119	0.001
Average Route #1	-	**0.152±0.029**	**0.097±0.166**
Route #2	#1	0.234	0.442
	#2	0.299	0.226
	#3	0.239	0.552
Average Route #2	-	**0.257±0.036**	**0.407±0.166**

Source: JRC, 2020

The NO_x emissions of Vehicle #2 did not exceed 0.3 g/kWh and were lower than the EURO VI engine certification limit (0.46 g/kWh). The NO_x emissions were highly repeatable among the different tests on both routes. Unlike Vehicle #1 there seems to be a difference in the NO_x emissions among the two routes. The more transient Route #2 exhibits higher NO_x values indicating slightly less effective operation of the catalyst under these conditions. Overall, the NO_x values of Vehicle #2 are in line with the reported range for five Euro VI HDVs tested under similar conditions [15]. It is important to note that the pollutant measurements were conducted under the fully warm operation of the engine and the aftertreatment system, thus it is expected that the catalyst would be fully effective. Cold start and NH_3 emissions have not been considered.

The CO emissions were rather low with average values ranging between 0.1-0.4 g/kWh. The CO emissions were one order of magnitude lower than the EURO VI engine certification limit (4.0 g/kWh). Current CO values are significantly lower than the ones reported for five Euro VI HDVs tested under similar conditions [15]. Like in the case of Vehicle #1, there is a substantial difference among the routes with the more transient exhibiting four times as high CO emissions than Route #1. However, the measurements over Route #1 come with a high uncertainty which is reflected by the high standard deviation over the three repetitions (Figure 7).

3.3.3 Vehicle #3

Table 26 presents the pollutant emissions recorded during the VTP test for Vehicle #3. Three tests were considered on both routes, while three more repetitions with increased payload (80%) on Route #4 were investigated. The average NO_x and CO values and standard deviation are also provided in Table 26.

Table 26. *Overview of pollutant emissions during the VTP for Vehicle #3*

	Test	NO_x [g/kWh]	CO [g/kWh]
Route #1	#1	0.206	0.025
	#2	0.153	0.480
	#3	0.109	0.031
Average Route #1	**-**	**0.156±0.049**	**0.179±0.261**
Route #4	#1	0.303	0.002
	#2	0.305	0.128
	#3	0.262	0.039
Average Route #4	**-**	**0.290±0.024**	**0.057±0.065**
Route #4 80% Payload	#1	0.344	0.321
	#2	0.266	0.007
	#3	0.265	0.128
Average	**-**	**0.292±0.045**	**0.152±0.158**

Source: JRC, 2020

The average NO_x emissions ranged between 0.15-0.30 g/kWh and did not exceed the EURO VI engine certification limit (0.46 g/kWh). The NO_x emissions were quite repeatable among the different tests on both routes. Once more, there is a significant difference in the NO_x emissions among the two routes. The more transient Route #4 exhibits twice as high NO_x emissions compared to Route #1. This can be attributed to the less effective operation of the catalyst under transient conditions. It seems that increasing the payload does not influence the NO_x emissions as there is practically no difference in the average values with 60% and 80% payload.

The average CO emissions ranged between 0.06-0.18 g/kWh and are well below the EURO VI engine certification limit (4.0 g/kWh). There seems to be a difference among the routes; however, Route #1 results come with a high uncertainty reflected by the high value of the StDev. Thus, no conclusion can be drawn regarding the influence of transient conditions on the CO emissions for this vehicle. It seems from Table 26 that the increase of payload leads to increase of CO emissions; however, once more Route #4 values with both payloads come with a high measurement uncertainty.

3.3.4 Vehicle #4

Table 27 gives an overview of the pollutant emissions recorded during the VTP test for Vehicle #4. Unfortunately, there was a technical issue with CO analyzer. Therefore only the NO_x emissions are available. Three tests were considered on both routes. Apart from the NO_x emissions of the individual tests, the average value of the emissions as well as the standard deviation of the repetitions is provided.

The average NO_x emissions ranged between 0.05-0.23 g/kWh and did not exceed the EURO VI engine certification limit (0.46 g/kWh). The NO_x emissions were quite repeatable among the different tests on both routes. The more transient route exhibits significantly higher NO_x emissions compared to Route #1. This is in-line with Vehicle #3 and is attributed to the less effective operation of the catalyst under transient conditions.

Table 27. *Overview of pollutant emissions during the VTP for Vehicle #4*

	Test	NO_x [g/kWh]	CO [g/kWh]
Route #1	#1	0.042	*
	#2	*	*
	#3	0.057	*
Average Route #1	**-**	**0.050±0.011**	*****
Route #4	#1	0.205	*
	#2	0.201	*
	#3	0.288	*
Average Route #4	**-**	**0.231±0.049**	*****

Source: JRC, 2020

4 Conclusions

The key conclusions of the experimental campaign and the subsequent analysis can be summarized as follows.

VTP Procedure and FC simulation

On-road tests were checked regarding their repeatability to understand the suitability of the proposed routes for each vehicle category. The main conclusions are summarized below:

- *VTP compliant tests were highly repeatable with all vehicles on all tested routes. The Standard Error (SE) of the WSFC was always below 2% This applies also to some tests which were not fully VTP compliant and exhibited minor deviations to the prescribed boundary conditions;*
- *A slightly higher Standard Error of the WSFC of both Coaches is observed over Route #2, which can be attributed to its higher transient nature compared to Route #1;*
- *A slightly higher Standard Error of the WSFC of both Medium Lorries is observed over Route #1, without any obvious explanation. However, the differences are not statistically significant;*
- *Increasing the payload from 60% to 80% does not affect the test repeatability in case of Vehicle #3.* It seems that a payload of approximately 60% is appropriate for the VTP of these vehicle categories*;*
- *Both Coaches showed a quite good agreement between the measured (FFM) and simulated (VECTO) FC values with the deviation being within ±5.5%;*
- *The C_{VTP} for both vehicles did not exceed 1.060 in any of the 14 tests and fulfilled the pass criterion defined in (EU) 2019/318 for Heavy Lorries categories 4, 5, 9 and 10;*
- *Medium Lorries did not exhibit consistent behavior. VECTO overestimated FC due to higher attribution of auxiliaries' electric load.* This part needs to be revisited in VECTO VTP Mode. *JRC simulations indicated that the application of realistic auxiliary loads significantly improved the accuracy of the simulation;*
- *Vehicle #3 exhibited much higher deviations between measured and simulated FC compared to Vehicle #4. This is attributed to non accurate input data in case of Vehicle #3 and the overestimation of auxiliary power demand;*
- *Overall, and taking into account the VECTO performance*, a less transient route seems more appropriate for the VTP of Coaches, while more transient routes seem more suitable for the VTP of Medium Lorries*;*
- *The current study demonstrated that it is possible to have a successful VTP test with; however, very high deviation between measured and simulated FC values. Therefore,* the Pass-Fail criteria as defined in Annex Xa shall be revised to include a maximum allowed deviation of 7.5% also to the down side ($C_{VTP} \geq 0.925$)*.*
- *All other elements of the draft Annex Xa seem to be appropriate for the VTP of the examined vehicle categories. Only minor adaptations in some technical details are required.*

FC and CO_2 measurements

FC data measured with different instruments were analysed to understand their suitability to provide accurate FC measurements. The main conclusions are summarized below:

- *The FC calculated from the PEMS CO_2 emissions is in good agreement with the FFM FC. Most measurements are within a 4% deviation, except for one test with Vehicle #4;*
- *Differences in the PEMS performance among the different routes are within the experimental uncertainty. The PEMS seems to perform equally well both under non-transient and highly transient conditions;*
- *The ECU FC readings are in good agreement with FFM FC. Most measurements are within a 5% deviation, except for all tests with Vehicle #4. There is no specific explanation regarding the high deviations observed with this vehicle. The issue is probably vehicle specific.*
- *The ECU seems to provide equally good FC results both under non-transient and highly transient conditions.*

Pollutant Emissions

The current report provides collected data on pollutant emissions to support analysis on how to monitor them during the VTP test. The key conclusions are summarized below:

- NO_x measurements were conducted under warm operation of the engine and the aftertreatment system, thus it is expected that the catalyst would be fully effective and emissions would be low;
- NO_x emissions were generally low and did not exceed the EURO VI engine certification limit (0.46 g/kWh), regardless of the vehicle and the tested route;
- The more transient routes exhibit higher NO_x emissions pointing to less effective operation of the catalyst under these conditions;
- For this analysis to be complete there is a need to also measure NH_3 emissions to avoid excessive use of SCR fluid;
- CO emissions were generally low and well below the EURO VI engine certification limit (4.0 g/kWh).

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List of abbreviations and definitions

ACEA	European Automobile Manufacturers' Association
AMT	Automatic Manual Transmission
CAN	Controller Area Network
C_{VTP}	Ratio of FC measured and simulated in the VTP
DPF	Diesel Particulate Filter
EC	European Commission
ECU	Electronic control unit
EGR	Exhaust Gas Recirculation
ESS	Engine Start Stop
FC	Fuel Consumption
FFM	Fuel Flow Meter
GPS	Global Positioning System
HDV	Heavy Duty Vehicle
JRC	Joint Research Centre
OBD	On-Board Diagnostics
OEMs	Original Equipment Manufacturers
PEMS	Portable Emissions Measurement System
PP1	Pilot Phase 1
PP2	Pilot Phase 2
PP3	Pilot Phase 3
SCR	Selective Catalyst Reduction of NO_x
SE	Standard Error
VECTO	Vehicle Energy consumption Calculation Tool
VELA	Vehicle Emissions Laboratories
VTP	Verification Testing Procedure
WHR	Waste Heat Recovery
WSFC	Wheel Specific Fuel Consumption

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