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Three-way catalyst performance using LPG with two different sulphur levels





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This report was prepared by: Joseph Woodburn, Jakub Dzida and Piotr Bielaczyc (BOSMAL)

Under the supervision of: Roland Dauphin (Concawe Science Executive)

Fuels@concawe.eu

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ABSTRACT

An experimental programme was carried out to determine the long-term impact of the level of sulphur present in LPG on the performance of three-way catalytic converters (TWCs) in terms of their elimination (conversion) of gaseous pollutants. Two TWCs were subjected to an engine dyno ageing procedure, with fuel of high (29 ppm m/m) or low (8 ppm m/m) sulphur content used for ageing. The performance of the TWCs was assessed before, during and after this ageing via emissions testing. Emissions testing was conducted on a passenger car (the type for which the two TWCs were designed), running on LPG fuel and tested on a chassis dynamometer over three different driving cycles. Emissions testing was performed in accordance with the European legislative method, supplemented by additional measurements and procedures, including continuous emissions measurements of undiluted gaseous pollutants.

With a single exception, the test vehicle met the applicable Euro 6 emissions limits when tested using its type approval procedure (NEDC), for both TWCs, at all ageing stages. The exception to this came in the form of a single NMHC emissions result, which in one test was found to be above the applicable legislative limit following 250 ageing cycles; the two other repetitions of this test under the same conditions showed NMHC emissions below with the Euro 6 limits, and the mean of these 3 tests was also below the Euro 6 limits. While emissions results obtained using the WLTP test procedure were not legally applicable to the test vehicle, results obtained using that procedure were also below the Euro 6 limits, in all cases, with no exceptions. The relatively low emissions results occurring even after extended ageing indicate high TWC conversion efficiency and durability under the specific ageing conditions tested.

The results showed that the ageing cycle caused a tendency for slightly lower TWC conversion efficiency (and thus slightly higher emissions results). It was found that differences in conversion of regulated pollutants were greatest at low operating temperatures (i.e. during and following cold start) and that differences were very limited under thermally stabilised conditions.

As regards the impact of fuel sulphur level on TWC conversion efficiency, overall there appeared to be no significant difference between the two test objects. In certain cases differences in performance were apparent, but sometimes the High-sulphur TWC outperformed its Low-sulphur counterpart. Even focusing on the results obtained from the cold start phases, no consistent, significant difference between the two test objects could be observed. It was concluded that the fuel's sulphur content had not exerted a clear, significant impact on TWC performance.

A possible explanation for this is that the high speed, high load driving simulated in the engine dyno ageing cycle (but which can also be met under real driving conditions, e.g. during highway driving) led to continuous desulphatation of the TWCs tested, hence leading to a potential non-harmful effect of sulphur content on the TWC conversion efficiency. A complementary study was performed to evaluate the relevance of this explanation (details in the appendix). It consisted in chemical analyses of the aged TWCs, using advanced laboratory methods. Unfortunately, this study remained inconclusive, as it were unable to directly link the sulphur level measured in the TWCs to their conversion efficiency loss. Consequently, lacking a clear and systematic explanation about the effect of sulphur on the TWC conversion efficiency, this study cannot be 100% conclusive regarding the harmful/non-harmful effect of sulphur content in LPG on the TWC conversion efficiency, even if the engine/vehicle tests tend to show that a higher sulphur content is not harmful.



KEYWORDS

LPG, three-way catalyst, sulphur, ageing, conversion efficiency

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1. DESCRIPTION AND IDENTIFICATION OF THE OBJECTS TESTED

The objects of the tests were two original aftertreatment systems (three-way catalysts, TWCs) dedicated to the Fiat Tipo 1.4 T-Jet LPG application. Denoted as 'Low S', and 'High S', the two test objects are identified in Table 1. The TWCs were purchased by BOSMAL and were delivered on the 7th of March 2018.

Parameter	TWC Low S	TWC High S	
Exhaust aftertreatment system type	Close-coupled three-way catalytic converter		
Approx. monolith volume [dm ³]	1.4		
Total PGM content [g/ft ³]; [g/dm ³]	150; 5.30		
PGM content (Pt:Pd:Rh)	0:145:5		
Intended application	Aftertreatment system for Fiat Tipo 1.4 T-Jet LPG (see Table 2)		

Table 1Data of the test objects

The platinum group metal (PGM) content of the test objects identified in Table 1 was typical in terms of the fact that no platinum (Pt) was used [1-4]. The ratio of palladium (Pd) to rhodium (Rh) of 145:5 (or 29:1) appeared to be higher than the average figure for that parameter (in comparison to the limited available information on other systems [1-2], [4-5]). The total PGM content appeared to be high compared to other Euro 6 TWC aftertreatment systems [1], [4-5]. A further consideration is the intended application of the test objects (bi-fuel LPG exhaust aftertreatment), for which typical specifications may differ slightly from that of mono-fuel petrol TWCs, especially in view of durability requirements and the elevated exhaust gas temperature that can result from combustion of LPG (compared to petrol). Notwithstanding the information presented in [1-5], as a general point, it should be noted that information on specification of typical market-available Euro 5/6 TWCs (for mono-fuel or bi-fuel applications) is rather limited. The specification of aftertreatment systems used in markets other than the EU (e.g. the USA) are of limited utility for comparisons with the test objects used in this study, due to several factors, namely: the existence of different emissions limits and test procedures in those markets; the tendency to use dual (close-coupled and underfloor) TWC systems; the very limited use of LPG for passenger cars in that market.

The two TWCs were tested on the specific vehicle type for which they were intended. Key technical data of the test vehicle are shown in Table 2. The test vehicle was supplied by BOSMAL and was not modified in any way, with the exception of mounting the two test objects identified in Table 1 for testing purposes.



Table 2Data of the test vehicle

Vehicle type	Passenger car, category M, segment C			
Commercial name	Fiat Tipo 1.4 T-Jet LPG			
Vehicle identification number	ZFA35600006K20252			
Engine type	Turbocharged 4-cylinder spark ignition, bi-fuel (LPG/petrol - indirect injection of both fuel types)			
Engine displacement [dm ³]	1.368			
Rated engine power [kW]	88			
Unladen mass [kg]	1320			
Emissions standard	Euro 6			
Aftertreatment system	1 × close-coupled TWC			
Year of manufacture	2017			
Date of registration	19.12.2017			
Mileage at start of testing [km]	4020			
Tyres	Continental ContiEcoContact 5 225/45 R17 V XL			
Details of vehicle fuelling system	Type approved as a bi-fuel vehicle (LPG/petrol). Engine cold start always occurs on petrol and switches over to LPG early in the test cycle (when LPG mode is selected).			



2. OBJECTIVE OF THE TESTS

Periodic chassis dynamometer testing in order to determine exhaust emissions and fuel consumption with the two test objects ('TWC Low S' and 'TWC High S') fitted to the test vehicle (in turn). Specifically, calculation of the test units' effectiveness in the elimination of regulated pollutants (i.e. conversion efficiency) before, during and following execution of an engine dyno TWC ageing procedure using two different LPG fuels, varying only in terms of sulphur content. Evaluations of the long-term impact were conducted, as fuel of varying sulphur content were used for ageing, while essentially sulphur-free fuel was used for testing. The inherent details of the test programme do not allow identification of the short-term emissions impacts of exposure to LPG fuel of varying sulphur content; this study examines long-term effects.



3. SCOPE AND METHODS OF THE TESTS

Exhaust emissions testing carried out in accordance with Regulation (EC) 715/2007 and Regulation (EC) 692/2008 - UNECE Regulation No. 83 and Regulation (EU) 2017/1151 in the range of exhaust emissions, carbon dioxide emissions and carbon balance fuel consumption measurements. Furthermore, a constant speed driving cycle was also used for emissions testing. The legislative test methods were used as the base procedure; additional measurements of emissions of undiluted pollutants from sampling points upstream and downstream of the TWC were also carried out. The sampling and measurement setup used for all emissions testing is shown in Figure 1

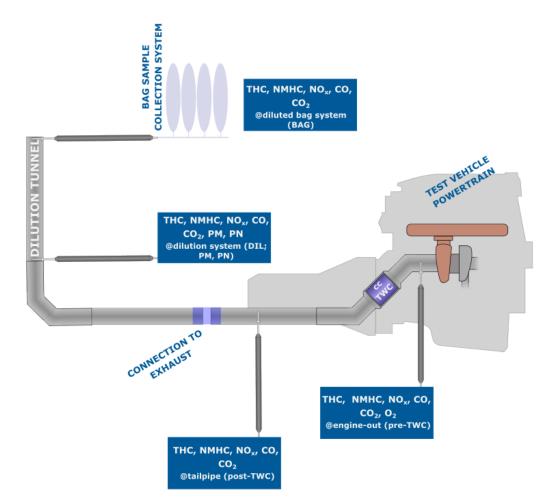


Figure 1 Schematic of the emissions sampling layout

For clarity, the test vehicle and chassis dynamometer are not shown in Figure 1. The test object ('CC TWC') is shown mounted to the engine in its close-coupled configuration. The vehicle's tailpipe is connected to the emission system as shown in the figure. The legislative measurement for exhaust emissions from vehicles of this type (i.e. bag measurement) was supplemented with continuous measurements at three points: pre-TWC, post-TWC and diluted, the latter including measurement of particulates (PM, PN).



Measurements relating to the above-mentioned points were carried out on the test vehicle with either the Low S or High S TWC installed, tested under closely-controlled laboratory conditions over predefined driving cycles. All emissions testing was conducted while the vehicle was fuelled with reference LPG (LPG A, as defined in Regulation (EU) 2017/1151). The activity matrix for each TWC is shown in Table 3. The emissions testing procedure was identical in every aspect for both TWCs; the ageing procedure used was also identical in both cases, with the only variable being the sulphur level of the LPG used for engine dyno ageing.

Table 3Activity matrix

Step No.	Activity	Details
1	Initial TWC preconditioning	12 consecutive repetitions of the EUDC cycle as preconditioning, performed using reference LPG; no emissions measurement
2	Initial emissions tests (0 cycle stage)	1 preconditioning cycle (WLTC) 3 WLTC emissions tests 3 NEDC emissions tests 2 constant speed tests
3	Ageing - 50 cycles	Execution of engine dyno ageing
4	Interim emissions tests (50 cycle stage)	1 preconditioning cycle (WLTC) 3 WLTC emissions tests
5	Ageing - 50 cycles	Execution of engine dyno ageing
6	Interim emissions tests (100 cycle stage)	1 preconditioning cycle (WLTC) 3 WLTC emissions tests
7	Ageing - 75 cycles	Execution of engine dyno ageing
8	Interim emissions tests (175 cycle stage)	1 preconditioning cycle (WLTC) 3 WLTC emissions tests
9	Ageing - 75 cycles	Execution of engine dyno ageing
10	Final emissions tests (250 cycle stage)	1 preconditioning cycle (WLTC) 3 WLTC emissions tests 3 NEDC emissions tests 2 constant speed tests

Step No. 1 represents the industry standard approach for preparing a completely fresh aftertreatment system for emissions testing, i.e. execution of 12 EUDC cycles, thereby covering a distance of 84 km at a mean speed of 62.6 km/h, with speeds reaching up to 120 km/h, but with a deceleration to standstill and a short period of idling occurring every 7 km. This preconditioning was performed using reference LPG as fuel (although the cold start event occurred on petrol). Note that the first item of each block of emissions testing (steps Nos. 2, 4, 6, 8, 10) consisted of running one WLTC test cycle with no emissions measurement, as preconditioning. This procedure was chosen to provide a balance between the need to prepare the test vehicle and stabilise the TWC for emissions testing and the desire to perform emissions testing on the aged TWC in its "as received" condition. The exact same test conditions and fuel were used for the preconditioning as for the subsequent emissions tests; preconditioning cycles always commenced from cold start.



Engine dyno ageing of the TWCs was carried out on an engine of identical type to the engine fitted to the vehicle used for emissions testing (see Table 2). The engine was run on a computer-controlled engine dyno, running a repeating cycle designed to simulate accelerated TWC ageing at high-speed, high-load vehicle operation. Figure 2 shows the essential characteristics of the cycle. Each cycle lasted just over 75 minutes and thus the full 250 cycles lasted approximately 314 hours.

During the cycles the engine dyno simulates the road load resistance which would be experienced by the vehicle. The distance covered by each cycle is 177 km and thus 250 cycles equates to 44,400 km. However, the highly demanding conditions recreated by the ageing cycle mean that an equivalence factor of 1.6 is applicable in order to convert to less demanding driving conditions. Thus, the total number of kilometres of typical driving may be estimated as being 44,400×1.6=71,040 km

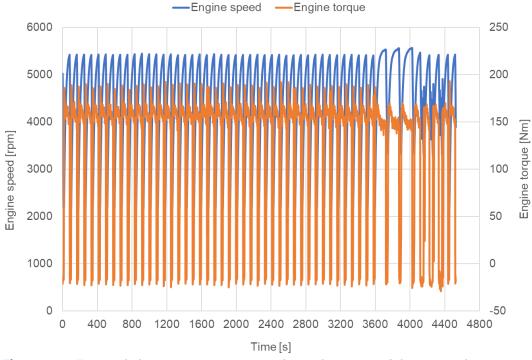


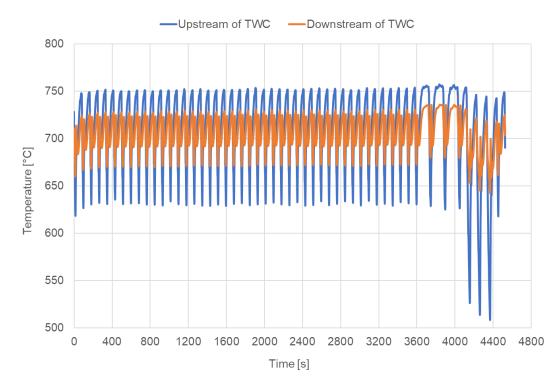
Figure 2 Essential characteristics (rotational speed, torque) of the engine dyno TWC ageing cycle used in this study

Figure 3 shows the temperatures of the exhaust gas during the ageing cycle. For the majority of each ageing cycle, the temperature of the exhaust gas entering the TWC oscillated between approximately 630° C and 750° C and the temperature of the exhaust gas downstream of the TWC oscillated between approximately 650° C and 730° C. The mean value of the temperature of the exhaust gas upstream of the TWC during each cycle was 709° C and the 75^{th} percentile temperature value was 745° C, meaning that temperatures exceeded that level for 25% of the total ageing time. The 99^{th} percentile temperature value was 755° C, meaning that temperatures exceeded that level for 25% of the total ageing time.

The temperature of the exhaust gas (and indeed of the monolith itself) is of paramount importance for thermal ageing as well as for deactivation (poisoning)



processes. Temperature and exhaust gas chemistry (i.e. λ , sulphur content) can affect the accumulation of inhibiting species such as S atoms and sulphur-based compounds, as well as their removal. A review of industry opinion and available literature [6-9] on Pd-Rh TWCs revealed that under conditions of alternating rich/lean conditions, the test objects used in this study would likely have begun to desulphate (i.e undergo physicochemical reactions leading to the removal of sulphur atoms and sulphur-bearing compounds from the catalytically active layer of the monolith) at a temperature within the range 650-700°C. As shown in Figure 3 and discussed below, such temperatures are achieved (and in fact exceeded) during the ageing cycle employed in this study and also during certain real-world driving scenarios.





The same engine was used for all ageing of the test objects, with engine oil and filter replacement carried out at regular intervals (approximately every 120 hours of engine operation). Ageing on the fuel with the lower sulphur content was carried out, in full, before exposing the engine to the fuel of higher sulphur content. A completely fresh set of spark plugs was used for ageing on each fuel. Each TWC was equipped with its own oxygen (λ) sensors, which were used during all ageing activities; the test vehicle was equipped with oxygen (λ) sensors, which were used for all emissions testing. Thus, the oxygen (λ) sensors used during emissions testing were not exposed to exhaust gas resulting from the ageing process (and vice-versa).

While λ was not monitored continuously during the ageing, certain key facts are known. During all portions of high load - i.e. the acceleration events - λ was always



<1, taking values in the range 0.75-0.8. During the relatively brief yet frequent periods of negative torque demand (fuel cut-off), λ obviously took values >>1. Thus, the ageing cycle's λ profile can be described as variable, but while the engine was being fuelled, λ generally took values <1, due to the cycle's inherent high power demand. Such a situation is typical for spark-ignition engines operating on LPG or petrol, while CNG-fuelled engines normally use much less enrichment, since such engines typically develop full power at λ >1.

In line with the project strategy, exhaust emissions were not measured during engine ageing. Stability of engine operation was monitored via continuous observations of temperatures, pressures, the fuel flow rate, etc.

Industry experts with considerable experience in the field of automotive aftertreatment systems for light duty vehicles were asked to comment on the ageing procedure. The consensus was that the engine speed and load profiles were typical for ageing procedures used on TWCs. However, the engine used in this study was in its production configuration, with no modifications to induce higher exhaust gas temperatures (i.e. injection of additional air, modification of valve timing) and thus the temperatures experienced by the test objects during ageing are somewhat lower than during ageing procedures conducted in other studies and reported elsewhere.

While lower temperatures reduce the severity of TWC ageing *(ceteris paribus)*, the temperatures encountered in the ageing cycle employed in this study have the advantage of not being artificially elevated, i.e. they could be experienced by a passenger car in normal real-world usage scenarios (i.e. high speed motorway driving, especially when driving uphill and/or with significant payload). Furthermore, it has been shown that the temperature experienced by the TWC monolith is, for the most part, appreciably higher than the temperature of the exhaust gas itself [10]. Thus, for the majority of the ageing cycle, the exhaust gas temperature can be considered a minimum temperature value for the thermal conditions experienced by the TWC monolith.

The ECU of the test vehicle reported two thermal parameters (both of which are modelled rather than directly measured). The temperature traces of these parameters over the cold start WLTC followed immediately by one EUDC (the second phase of the NEDC) are shown in Figure 4. (Note that the speed trace shown in Figure 4 is merely a demonstration of temperature trends and was not used for any emissions testing.)



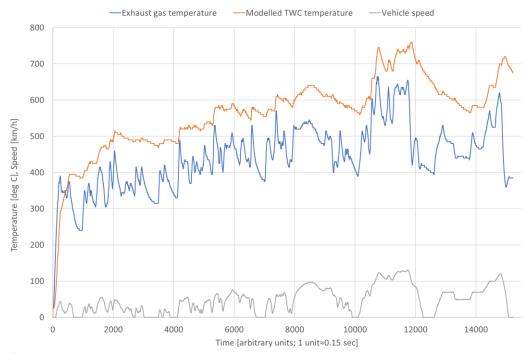


Figure 4 Profile of the temperature of the exhaust gas and the TWC monolith reported by the test vehicle's ECU over the WLTC and the EUDC phase of the NEDC.

As is evident from Figure 4, the temperature of the TWC very quickly comes to exceed that of the exhaust gas itself following cold start. The temperatures experienced by the TWC monolith during the 4th phase of the WLTC (10,000 to 12,200 time units on the x-axis) reached values up to 750°C and were $\geq 650°C$ for approximately 2.5 uninterrupted minutes. Over the EUDC (10,000 to 12,200 time units on the x-axis) the maximum TWC monolith temperature reached was just over 710°C (following the acceleration to 120 km/h); the previous acceleration (from 70 to 100 km/h) caused temperatures which reached approximately 640°C. The veracity and accuracy of the temperature modelling approach is discussed in [10] - while there may be overestimations of the temperature under non-stoichiometric conditions, generally speaking, the modelled temperature is considered accurate and valid.

The two test objects (the 'Low S' and 'High S' TWCs) were subjected to the ageing procedures mentioned above, using two fuels which differed only in terms of sulphur content. A third fuel was used for emissions testing. All three fuels are identified in Table 4.



Parameter / Fuel name LPG Low S		LPG High S	Reference LPG A
Fuel type	Commercially available LPG	Commercially available LPG	Certified reference fuel
		Engine dyno ageing of TWC High S	Chassis dyno emissions testing of TWC Low S and TWC High S
Total fuel sulphur content according to fuel certificate [mg/kg]	8.2	29.0	<1.0
Odour	Imperceptible	Perceptible	Not assessed
Odorant added?	Unknown	Yes	No
Assumed main source(s) of sulphur-bearing compounds	Crude oil	Crude oil, odorant	Trace impurities
Fuel certificates	Appendix 1, Appendix 2	Appendix 3, Appendix 4, Appendix 5, Appendix 6	Appendix 7, Appendix 8

Table 4 Data of the LPG fuels used in this test programme

Reference LPG A refers to the fuel specification given in Regulation (EU) 2017/1151, Annex IX, section A., point 1., Type: LPG, column 'Fuel A'. The same fuel specification is also shown in UNECE Regulation No. 83, Annex 10a, point 1.1, Type: LPG, column 'Fuel A'. Appendix 7 shows the standard certificate provided by the reference fuel supplier; Appendix 8 shows the results of detailed analyses of fuel parameters, including sulphur content. Reference LPG fuel was chosen to ensure that LPG of known, closely-controlled specification was used for all emissions tests, thereby reducing uncertainty and potential test-to-test variability. (Regular refuelling of the test vehicle with commercially available LPG would have introduced a significant source of uncertainty to the emissions measurements.) While type approval requirements stipulate that LPG-fuelled vehicles must be tested on both gaseous reference fuels (LPG A and LPG B), this study did not employ the full type approval procedure and thus it was deemed neither necessary nor technically appropriate to perform testing on both reference LPG fuels.



4. DESCRIPTION AND RESULTS OF THE TESTS

4.1. MEASURING EQUIPMENT

The specifications of the measuring equipment are shown in Table 5; the test vehicle undergoing emissions testing is shown in Fig. 5. (See also Figure 1).



Device Name	Туре	Identifying No.	Measurement range	Accuracy of measuremen t
Chassis Dynamometer 2WD	AVL Zöellner	X/1141/BHT	0 - 200 km/h 0 - 10 kN	± 0.05 % ± 0.1 %
Exhaust Emission Analysis System:	AVL AMA i60	X/2624/BHT		
CO Dilute	AVL IRD i60 CO L	L/2625/BHT	0 - 5 000 ppm	\pm 2% of the
CO ₂ Dilute	AVL IRD i60 CO ₂ H	L/2626/BHT	0 - 20%	measuring point or
NO _x Dilute	AVL CLD i60 LHD	L/2628/BHT	0 - 1 000 ppm	± 1% of the full scale
THC Dilute	AVL FID i60 LHD	L/2629/BHT	0 - 1 000 ppm	
CH₄ Dilute	AVL FID FID i60 LHD	L/2630/BHT	0 - 1 000 ppm	
CO High Pre	AVL IRD i60 CO H	L/2775/BHT	0 - 10 %	
CO Low Pre	AVL IRD i60 CO L	L/2781/BHT	0 - 1000 ppm	
CO ₂ Pre	AVL IRD i60 CO2	L/2776/BHT	0 - 20 %	
NO _x Pre	AVL CLD i60	L/2778/BHT	0 - 6000 ppm	
THC Pre	AVL FID i60	L/2779/BHT	0 - 37000 ppm C1	
CH₄ Pre	AVL Cutter FID i60	L/2780/BHT	0 - 20000 ppm C1	± 2% of the
CO High Post	AVL IRD i60 CO H	L/2785/BHT	0 - 10 %	measuring point
CO Low Post	AVL IRD i60 CO L	L/2784/BHT	0 - 1000 ppm	
CO ₂ Post	AVL IRD i60 CO2	L/2786/BHT	0 - 20%	
NO _x Post	AVL CLD i60	L/2788/BHT	0 - 6000 ppm	
THC Post	AVL FID i60	L/2789/BHT	0 - 10000 ppm	
CH₄ Post	AVL Cutter FID i60	L/2790/BHT	0 - 3000 ppm	

Table 5Data of measuring devices



CVS Sampling System ESU with	CVS i60 LD LE		2 - 20 m ³ /min	± 2%
dilution tunnel and PM sampling system DLS	PSS i60 SD	X/2631/BHT	50 - 100 l/min	± 5%
Microbalance	Sartorius M5P000V001	B/1915/BHT	0 - 2.7 g	0.0001 mg
Particle Number Counter	APC 489	L/2636/BHT	0 - 50 000 particles/cm ³	10%
Temperature and	VAISALA HMT 333	L/2637/BHT	-40 - +80 °C	± 0.2 °C
humidity transducer			0 - 100% relative humidity	± 1%
Electronic Barometer	VAISALA PTB 330	F/1543/BHT	500 - 1100 hPa	± 0.15 hPa



Figure 5 Fiat Tipo 1.4 bi-fuel vehicle during emission measurements in climate-controlled laboratory with an AVL Zöellner chassis dynamometer (2WD)



4.2. TEST RESULTS

4.2.1. Results of measurements of regulated exhaust emissions, carbon dioxide emissions and fuel consumption

All emission tests were carried out using the chassis dyno loading obtained from matching road load data provided by the vehicle manufacturer using the coast down method. The target road load data (F0,F1,F2) were the same for WLTP and NEDC testing, but in the case of WLTP testing a different inertia setting was used (taking into consideration the actual mass of the vehicle, mass representative of vehicle payload and the inertia of rotating powertrain components), in line with the requirements of Regulation (EU) 2017/1151. The inertia settings and final chassis dyno loading coefficients are presented in Table 6. Tyre pressure was checked - and, if necessary, adjusted - before the precondition cycle that commenced each batch of emissions testing. Thus, a constant level of tyre pressure was maintained through the test programme. Vehicle running resistance was checked following the preconditioning cycle that commenced each batch of emissions tests. Small differences in the running resistance were detected, but in view of their limited magnitude, it was decided not to change the chassis dyno loading and thus the same settings were used throughout the test programme (on both test objects).

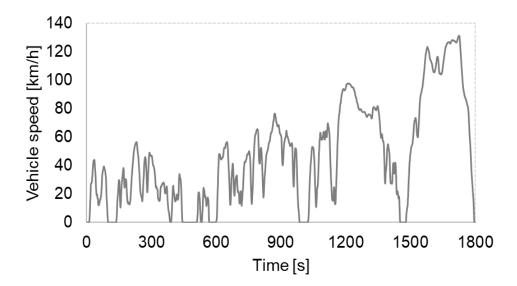
Inertia	Chassis dyno loading coefficients			Power absorption by the chassis dynamometer at 80 km/h
	WLTP and consta			int speed testing
	F0	F1	F2	
[kg]	[N]	[N/(km/h)]	[N/(km/h) ²]	[kW]
1509	45.1	-0.87	0.0390	5.0
			NEDC t	resting
	F0	F1	F2	
[kg]	[N]	[N/(km/h)]	[N/(km/h) ²]	[kW]
1360	21.0	-1.13	0.0404	4.2

Table 6Data of load coefficients

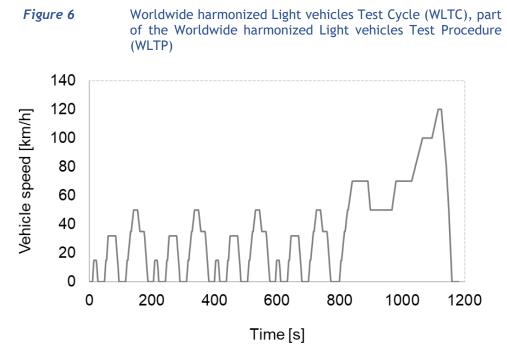


As outlined in Table 3, a single WLTC cycle was executed as preconditioning before each batch of testing commenced. All emissions tests commenced from cold start at an ambient temperature of 23°C and 40% relative humidity. To ensure complete cooling of the entire powertrain (including TWC), the standing time between periods of engine operation for cold start tests (WLTC, NEDC) was always ≥11 hours. All cabin accessories were turned off, including the ventilation system and the vehicle's lights were in 'Auto' mode. The cold start test cycles (NEDC, WLTC) were commenced with the test vehicle's battery fully charged; the battery was not charged immediately before the constant speed tests, which commenced from a hot start. The vehicle was always tested in LPG mode; all cold start events occurred with the engine running on petrol and the fuel supply was switched over to LPG automatically by the vehicle's ECU (i.e. with no driver intervention). It should be noted that such a fuelling strategy is typical for European petrol-LPG bifuel vehicles. Fuel switchover (petrol \rightarrow LPG) occurred approximately 56 seconds after engine cranking when running over the WLTC and NEDC driving cycles, with very limited differences in the timing of fuel switchover between tests (regardless of the test cycle). During the constant speed tests there was no cold start and thus no fuelling with petrol while emissions measurements were being carried out. The vehicle's two original oxygen (λ) sensors were used for all emissions testing on both test objects - i.e., the sensors used during engine dyno ageing were not used for any emissions testing activity.

Measurements of exhaust emissions were carried out over the well-known, industry standard WLTC and NEDC driving cycles (Fig. 6 and Fig. 7) and also using a customised constant speed test procedure. The constant speed test procedure was conducted with the vehicle already fully warmed up (by running the NEDC test cycle, followed by a smooth, gradual acceleration to 80 km/h, application of 5th gear and approximately 9 minutes' driving at 80 km/h in 5th gear). Thereafter, emissions measurements were performed over two periods, while continuing to drive at a constant speed of 80 km/h in 5th gear. The distance covered during each measurement period was approximately 10 km, during which time the driver attempted to keep vehicle speed as constant as possible, with minimum throttle fluctuations.









Tables 7 to 20, which can be found in the appendix, present exhaust emissions results for the test fuels obtained from the test vehicle, for the test cycles employed and their component phases. The aforementioned tables include the results of legislative measurements obtained via the CVS-bag method, diluted exhaust emissions measurements and results from measurements of undiluted exhaust emissions upstream and downstream of the TWC. Particulate matter emissions, while not regulated in the EU for this vehicle type, are also shown in terms of mass (PM) and number (PN); PM results are available for the entire test cycles, while PN results are available for the entire test cycles, and their component phases. Carbon dioxide emissions and fuel consumption results calculated according to the legislative carbon balance method are also shown. The tables show the calculated mean and standard deviation from the obtained emissions results, as well as values of standard type A uncertainty obtained by means of statistical analysis, calculated using the following formula:

$$u_A^2(M) = \frac{\sqrt{\frac{1}{n-1}\sum_{j=1}^n (x_j - \overline{x})^2}}{\sqrt{n}}$$

where:

 $u_{A}^{2}(M) = type A$ evaluation of standard uncertainty (for measured quantity M, where M represents regulated emissions, CO_{2} or fuel consumption),

n = number of tests,

 x_j = result from test j,

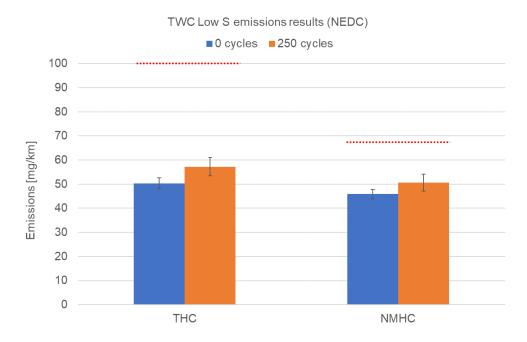
X = arithmetic mean of all tests.

Figures 8 to 31 show emissions results for the based on the legislative bag measurements of regulated compounds THC, NMHC, CO and NO_x ; results are shown

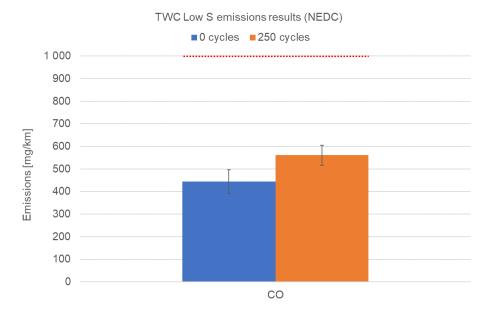


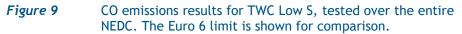
for the entire NEDC and the initial, cold start phase of that cycle (UDC), as well as the entire WLTC and the initial, cold start phase of that cycle (WLTC Low). The graphic representations' error bars are defined as the standard type A uncertainty values shown in Tables 7 to 20.













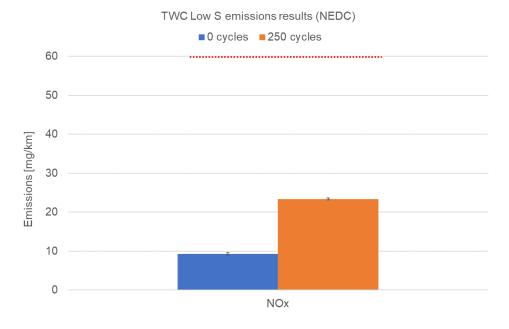


Figure 10 NO_x emissions results for TWC Low S, tested over the entire NEDC. The Euro 6 limit is shown for comparison

As shown above, execution of 250 ageing cycles using low sulphur fuel caused measurable increases in emissions of THC, NMHC, CO and NO_x when tested over the NEDC. Emissions remained below the applicable Euro 6 limits following 250 ageing cycles - by a considerably margin the case of THC, CO and NO_x and by a smaller margin the case of NMHC. Taking into account the number of repeat tests (n=3) and the derived uncertainty of the results, differences between the THC, NMHC and CO results at 0 cycles and at 250 cycles were limited. The difference was more apparent for NO_x, with the difference being significantly larger than the uncertainty in the mean results. Similar trends were observed during the first, cold start phase of the NEDC - the UDC, as shown in Figures 11-13. While measured emissions of THC, NMHC and CO were all higher at the 250 cycle stage than at the 0 cycle stage, the magnitude of the difference was small in comparison to the uncertainty of the results, while NO_x showed a clear difference, with emissions more than doubling following 250 ageing cycles.



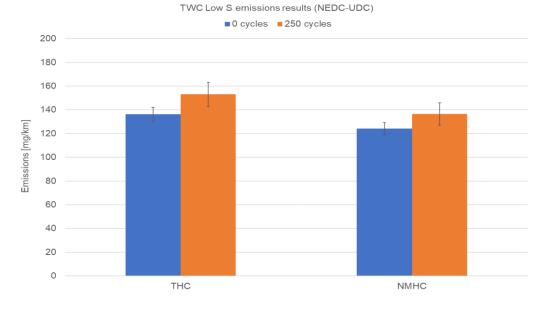


Figure 11 THC and NMHC emissions results for TWC Low S, tested over the UDC phase of the NEDC.



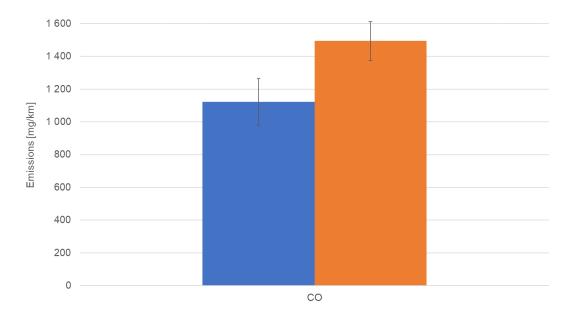


Figure 12 CO emissions results for TWC Low S, tested over the UDC phase of the NEDC.

19



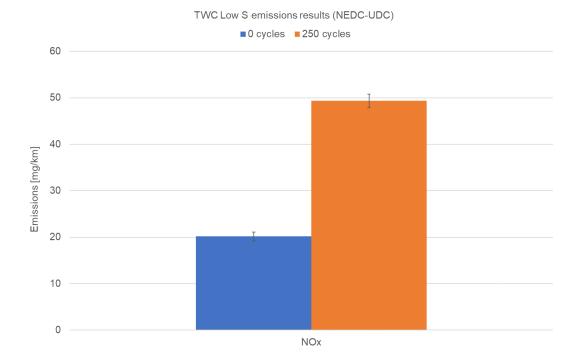


Figure 13 NO_x emissions results for TWC Low S, tested over the UDC phase of the NEDC.

WLTC results as a function of the number of ageing cycles are available at higher resolution (as interim testing was conducted over the WLTC only). As shown in Figures 14-15, THC, NMHC, and CO increased monotonically from 0 to 100 cycles, while the result at 175 cycles was essentially indistinguishable from the result at 100 cycles. The results for THC and NMHC in fact decreased at the 250 cycle stage, being at a level close to that of the 50 cycle stage. For CO, the trend was slightly different, as emissions reached a plateau starting at 100 cycles and there was no significant variation for the next two measurement points (175, 250 cycles). As shown in Figure 16, for NO_x, a noticeable increase occurred between 0 and 50 cycles, but thereafter emissions fell somewhat at 100 cycles, while emission sat 175 cycles were slightly higher and indistinguishable from each other. While the Euro 6 emissions limits are not directly applicable to this test vehicle when tested over the WLTC, it is noteworthy that those limits were not exceeded at any ageing stage.



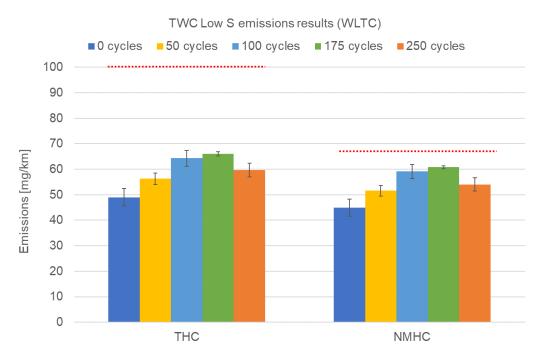


Figure 14 THC and NMHC emissions results for TWC Low S, tested over the entire WLTC. The Euro 6 limits are shown for information only.

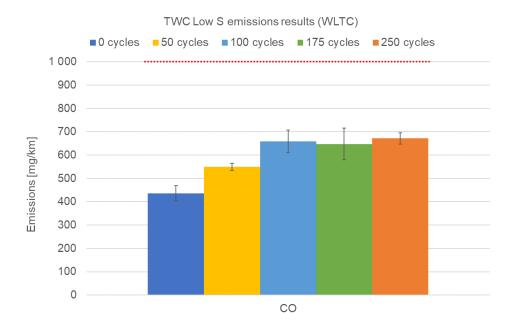


Figure 15 CO emissions results for TWC Low S, tested over the entire WLTC. The Euro 6 limit is shown for information only.

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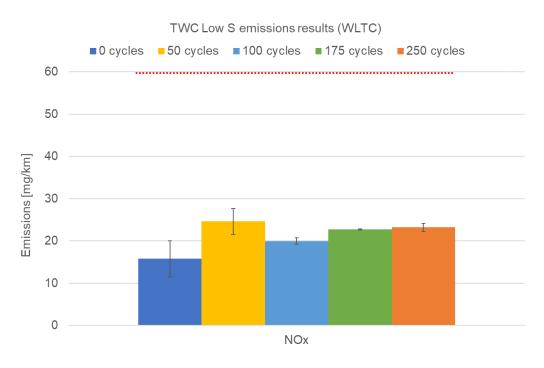


Figure 16 NO_x emissions results for TWC Low S, tested over the entire WLTC. The Euro 6 limit is shown for information only.

Partially contrasting trends were observed the first, cold start phase of the WLTC (i.e. Low phase), as shown in Figures 17-19. THC and NMHC showed the same trend as over the entire WLTC (i.e. a monotonic increase up to 100 cycles, a very small increase at 175 cycles and a marked decrease in emissions at 250 cycles, meaning that results at 250 cycles were essentially the same as at 50 cycles. CO and NOx showed interrupted monotonic increases in the range 0-250 cycles, although the rate of increase slowed significantly after the first 50 cycles. Differences in CO and NOx emissions between the 175 and 250 cycle stages appeared to be insignificant.



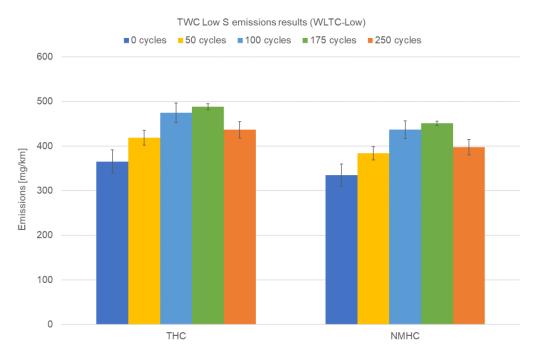


Figure 17 THC and NMHC emissions results for TWC Low S, tested over the Low phase of the WLTC.

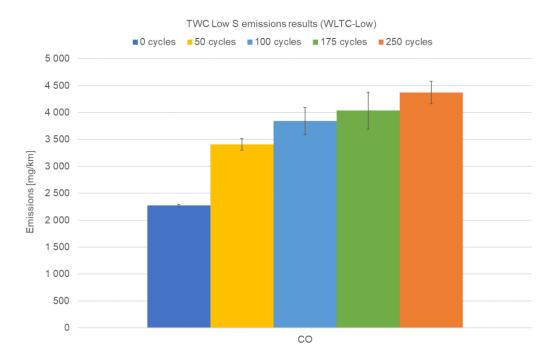
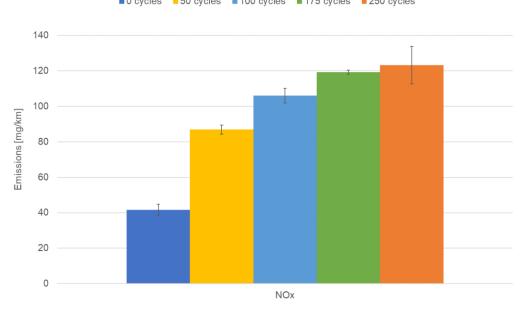


Figure 18 CO emissions results for TWC Low S, tested over the Low phase of the WLTC



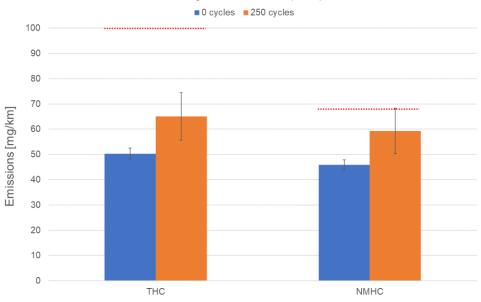


TWC Low S emissions results (WLTC-Low) • 0 cycles • 50 cycles • 100 cycles • 175 cycles • 250 cycles

Figure 19 NO_x emissions results for TWC Low S, tested over the Low phase of the WLTC.

Results for the test object aged using fuel of high sulphur content (TWC High S) are presented in Figures 20-31. When tested over the NEDC, there was a clear increase in emissions of THC, NMHC, CO and NOx following 250 ageing cycles. In the case of NMHC, mean emissions at the 250 cycle stage were very close to the Euro 6 limit (and in fact exceeded that limit during one test). Specifically, the NMHC emissions result during test L1-0004 (NEDC test number 3 at the 250 cycle stage on TWC High S); that result is shown in red in Table 14. The NMHC results for NEDC test numbers 1 & 2 at the 250 cycle stage were significantly below the Euro 6 limit, such that the mean NMHC result of all three NEDC tests was 59 mg/km, i.e. 87% of the limit. Given the generally high variability of the emissions results at the 250 cycle stage, reflected in the standard deviation and type A uncertainty values, this result should be treated with caution. Further testing would be required to fully determine NMHC emissions compliance with the Euro 6 limit for TWC High S at the 250 cycle stage. It should also be noted that the NMHC emissions during test L1-0004 were elevated for the UDC (cold start, urban) phase of the NEDC; emissions results for the EUDC (extra-urban) phase were very low and essentially identical for all three NEDC tests at the 250 cycle stage for the High S test object. The measured engine-out (pre TWC) NMHC emissions for test L1-0004 were comparable to those from NEDC test numbers 1 & 2 at the same stage; the temperature traces for the three NEDC tests in question also revealed no significant differences.





TWC High S emissions results (NEDC)



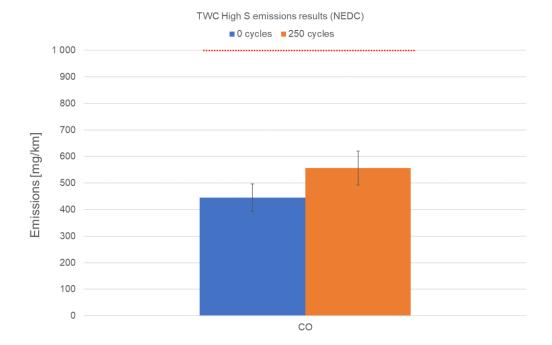


Figure 21CO emissions results for TWC High S, tested over the entire
NEDC. The Euro 6 limit is shown for comparison



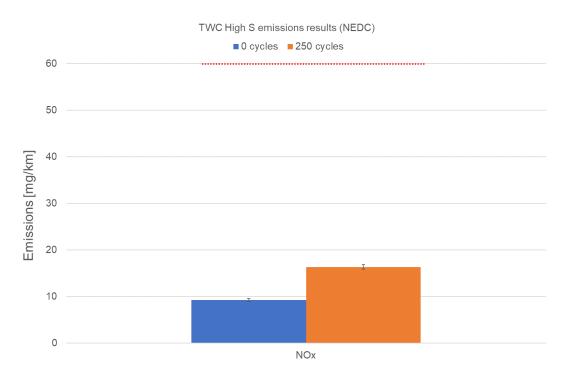


Figure 22 NO_x emissions results for TWC High S, tested over the entire NEDC. The Euro 6 limit is shown for comparison.

Trends observed over the UDC phase of the NEDC were essentially identical, with clear increases at 250 cycles, with particularly large relative increases observed in the case of NO_x .

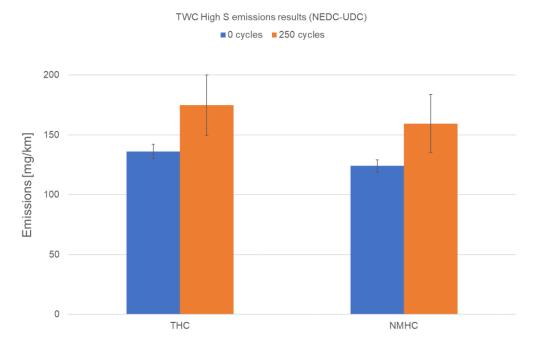
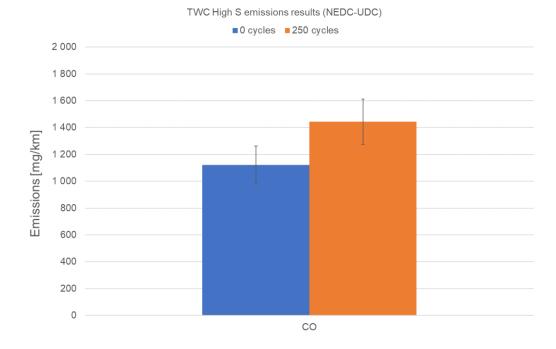


Figure 23 THC and NMHC emissions results for TWC High S, tested over the UDC phase of the NEDC.







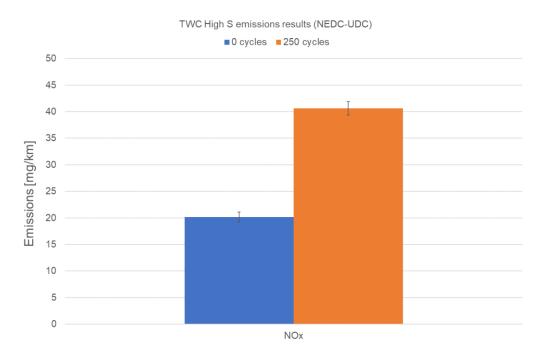
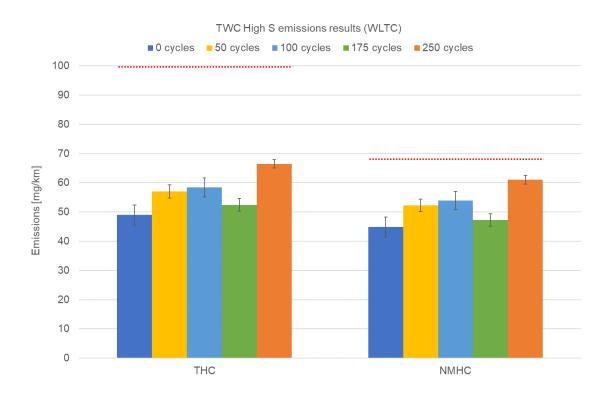


Figure 25 NO_x emissions results for TWC High S, tested over the UDC phase of the NEDC.

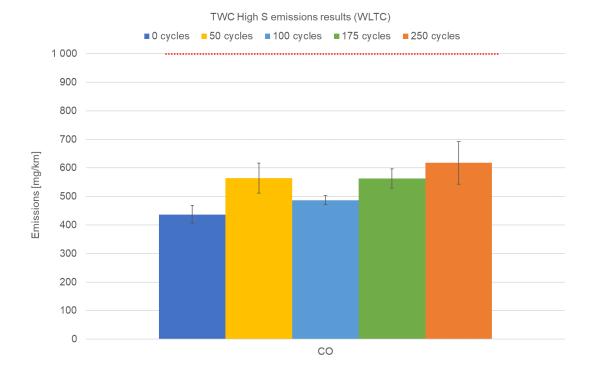


When tested over the WLTC, the following emissions trends were observed, as shown in Figures 26-31. For THC and NMHC, emissions increased for 0 to 50 cycles, but the result for 100 cycles was essentially identical to that at 50 cycles. Thereafter, at 175 cycles emissions fell to a level between that of 0 and 5-0 cycles, but a substantial increase occurred between 175 and 250 cycles. CO emissions increased noticeably from 0 to 50 cycles, fell at 100 cycles and then increased at 175 and 250 cycles (for which differences in the emissions level were of limited significance). For NO_x emissions there was little variation between the ageing stages, with the exception of 100 cycles, which showed the highest emissions results. NOx results from the final two stages (175, 250) were essentially identical.

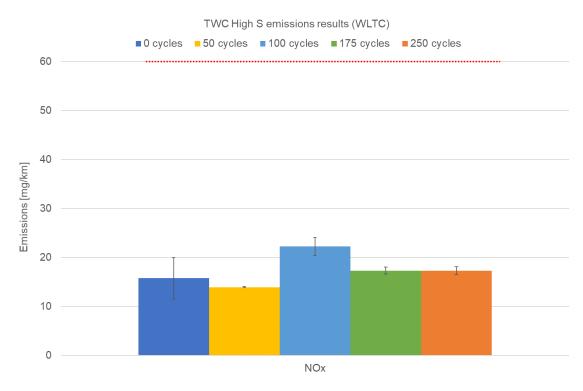




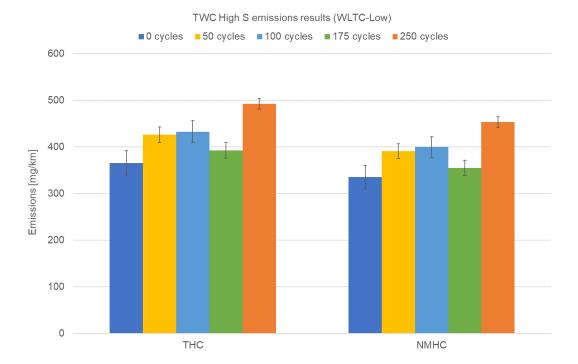














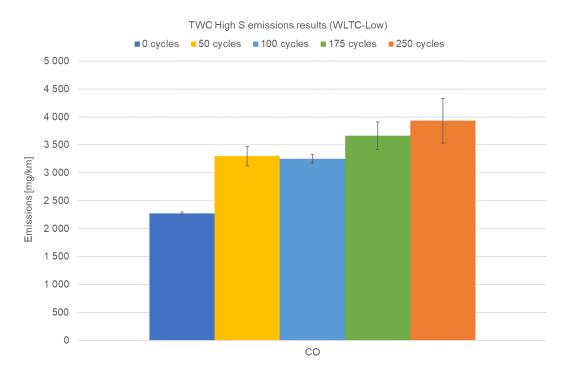


Figure 30 CO emissions results for TWC High S, tested over the Low phase of the WLTC.



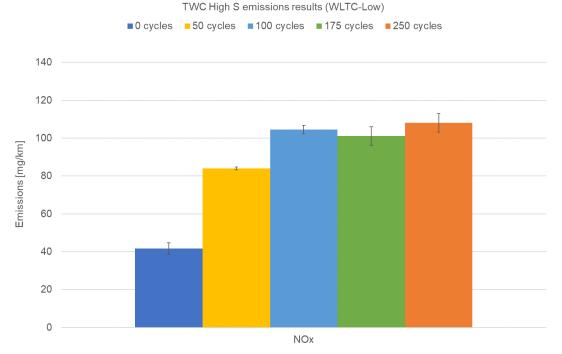


Figure 31 NO_x emissions results for TWC High S, tested over the Low phase of the WLTC.

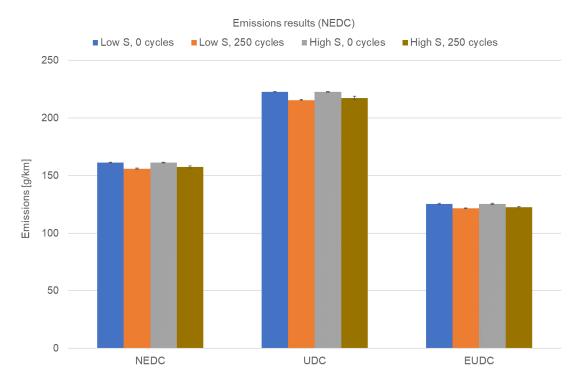
Emissions other than regulated gaseous emissions are discussed below, together with fuel consumption.

Emissions other than regulated gaseous emissions are discussed below, together with fuel consumption.

Emissions of particulate matter (by mass and number; PM and PN) were both stable and consistently relatively low throughout the entire test programme, with no apparent correlation to the number of ageing cycles. It should be noted that vehicles of the type used for testing are not subject to PM or PN limits in the EU. The test vehicle's mean PM and PN results met the EU limits for M-category vehicles, over both test the NEDC and WLTC, with both test units mounted. PM and PN emissions were lower still for constant speed testing, due to the lack of cold start in that test procedure. Due to the above considerations, PM and PN emissions are not shown graphically, but numerical results are presented in Tables 7-20.

Carbon dioxide emissions (Figures 32 and 33) and fuel consumption (Figures 34 and 35) were relatively stable during the test programme. There was a slight tendency for those parameters to fall as ageing progressed, but the magnitude of the differences was small (approximately 3% when comparing 0 cycles to 250 cycles). As the test programme was conducted, vehicle mileage increased by some 45% compared to the mileage at start of testing, which would generally be expected to cause running resistance to reduce somewhat. Nevertheless, the periodic coast down verifications showed very limited differences in running resistance and, as mentioned previously, no changes were made to the chassis dyno loading during testing. A further tendency of note relates to the fact that as emissions of THC and CO increase, CO_2 emissions fall slightly, since less CO_2 is formed in the TWC





via the oxidation of THC and CO. The observed decreases in CO_2 emissions can be attributed to the combined impact of the two aforementioned effects.

Figure 32 CO₂ emissions results for TWC Low S and TWC High S, tested over the NEDC and its component phases.



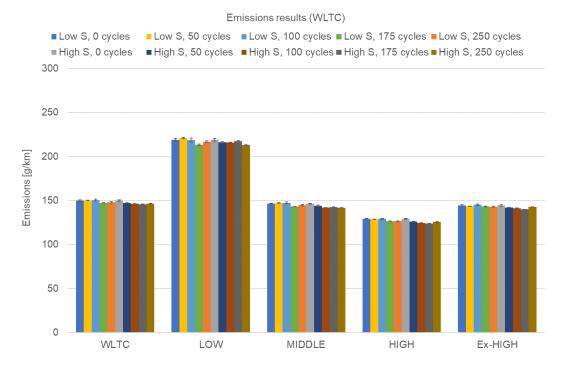


Figure 33 CO₂ emissions results for TWC Low S and TWC High S, tested over the WLTC and its component phases.

Fuel consumption calculated according to the legislative carbon balance method takes emissions of THC and CO (as well as CO_2) into consideration. Thus, the slight fall in fuel consumption as ageing progressed can be attributed to the slight reduction in friction that occurred as vehicle mileage increased, together with the effects resulting from test-to-test variations which are unavoidable when using a human driver. As a final point, the number of repeat tests NEDC and WLTC testing (n=3 in both cases) should be borne in mind.



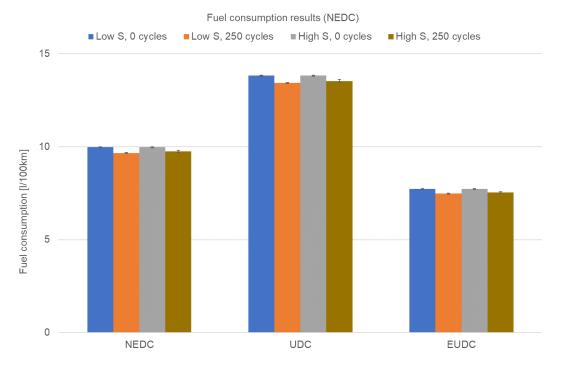


Figure 34 Fuel consumption results for TWC Low S and TWC High S, tested over the NEDC and its component phases.

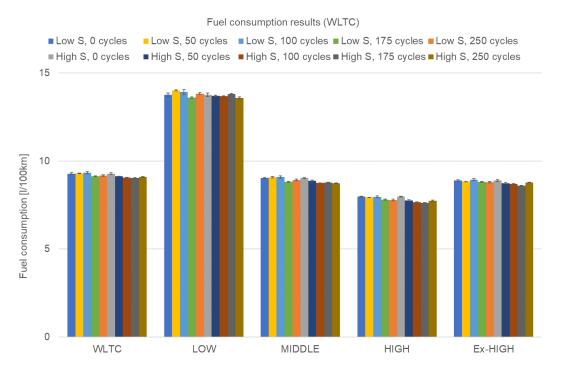


Figure 35 Fuel consumption results for TWC Low S and TWC High S, tested over the WLTC and its component phases.



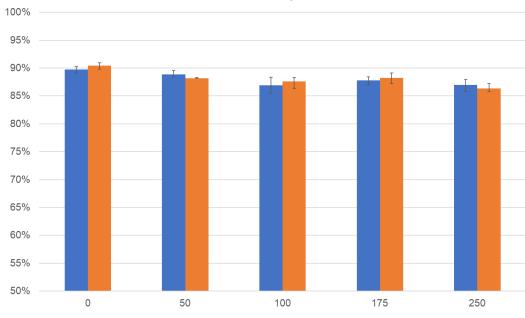
4.2.2. Results of calculated TWC conversion efficiency

Tables 7 to 20 show the test objects' conversion efficiency, calculated in two ways:

- by comparing the measurements of undiluted exhaust emissions upstream with the CVS-bag measurements of diluted exhaust emissions of the TWC (labelled 'pre-bag'),
- by comparing the measurements of undiluted exhaust emissions upstream and downstream of the TWC (labelled 'pre-post').

Figures 36 to 55 show TWC conversion efficiency ('pre-post', as defined above); the graphic representations show the mean results, with error bars defined as the minimum and maximum measured values (not type A uncertainty).

WLTC results are available at higher resolution, as shown in Figures 36-43. For THC, NMHC and CO, the raw results showed no overall trend as to which test object performed better (i.e. Low S<High S and High S<Low S both occurred), but there was an observable overall trend for a gradual and quasi-monotonic decrease in conversion efficiency as ageing progressed from 0 to 250 cycles, visible in the figures below.

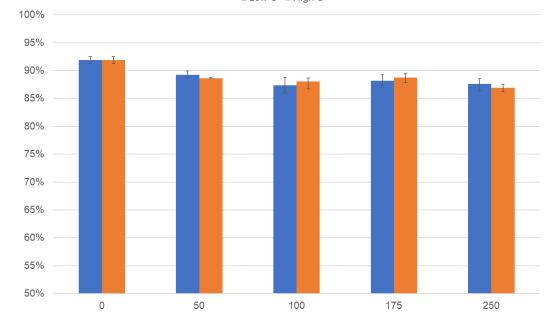


THC TWC effectiveness (WLTC) ■ Low S ■ High S



TWC conversion efficiency calculated from THC emissions results for both test objects, tested over the entire WLTC.

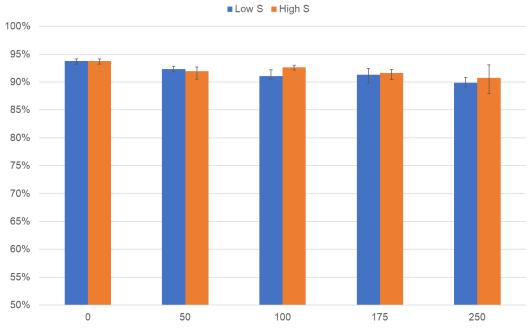




NMHC TWC effectiveness (WLTC)

Low S High S

Figure 37 TWC conversion efficiency calculated from NMHC emissions results for both test objects, tested over the entire WLTC.



CO TWC effectiveness (WLTC)

Figure 38

TWC conversion efficiency calculated from CO emissions results for both test objects, tested over the entire WLTC.



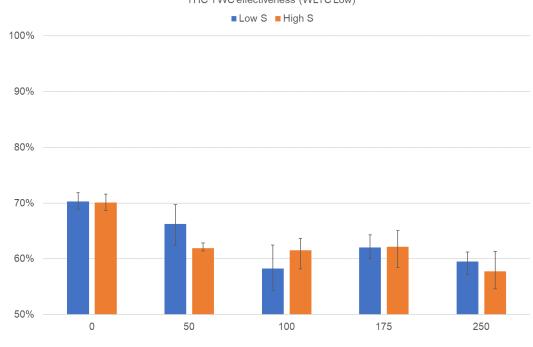
For NO_x , the picture was somewhat more complicated, as the High S TWC appeared to outperform its counterpart at three ageing stages (50, 175 and 250 cycles). The trend was non-monotonic and the difference between 0 and 250 cycles was limited, especially in the case of TWC High S.





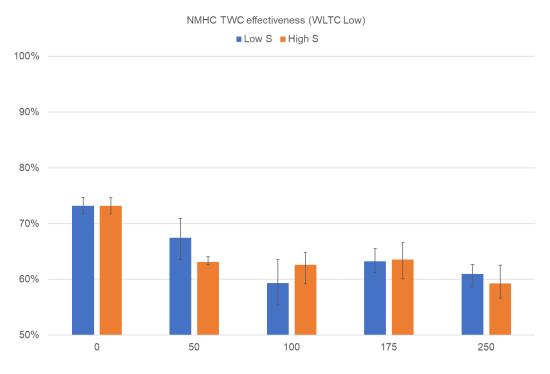
As shown in Figures 40-43, trends were broadly similar over the WLTC's Low phase, but differences were numerically much greater and generally more evident, due to the much lower conversion efficiency during the Low phase, which contains the cold start event (meaning the TWC's temperature is equal to ambient temperature at the very beginning of the test).





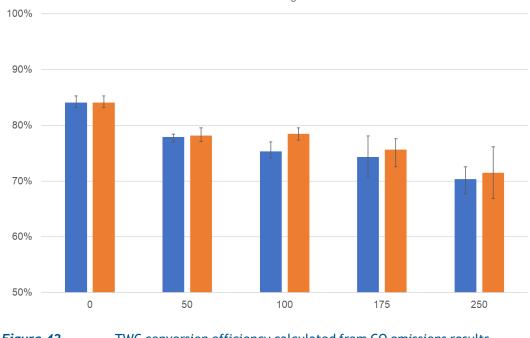
THC TWC effectiveness (WLTC Low)

Figure 40 TWC conversion efficiency calculated from THC emissions results for both test objects, tested over the Low phase of the WLTC.









CO TWC effectiveness (WLTC Low)

■Low S ■High S



TWC conversion efficiency calculated from CO emissions results for both test objects, tested over the Low phase of the WLTC.

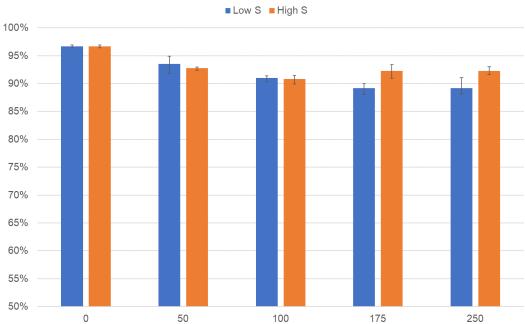




Figure 43

TWC conversion efficiency calculated from $\rm NO_x$ emissions results for both test objects, tested over the Low phase of the WLTC.



As regards conversion efficiency over the NEDC, only two sets of results are available (0 and 250 cycle stages), as shown in Figures 44-47. At the 0 cycle stage the agreement between the two test objects was excellent, as expected. At the 250 cycle stage, conversion efficiency for THC, NMHC and CO was noticeably lower than at 0 cycles, with very limited differences between the two test objects. For NO_x the situation was similar, with the exception that conversion efficiency was noticeably higher for the High S TWC.

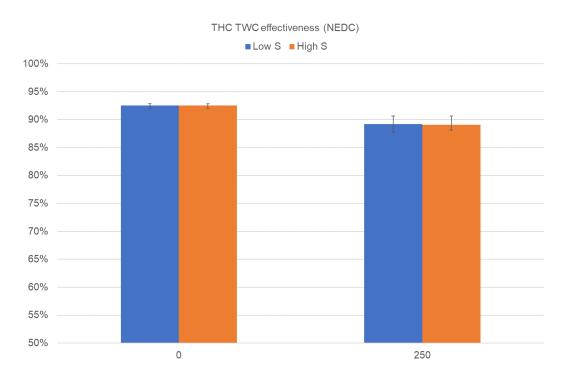
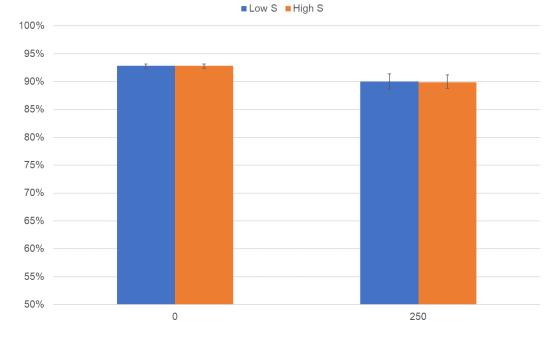


Figure 44 TWC conversion efficiency calculated from THC emissions results for both test objects, tested over the entire NEDC.





NMHC TWC effectiveness (NEDC)



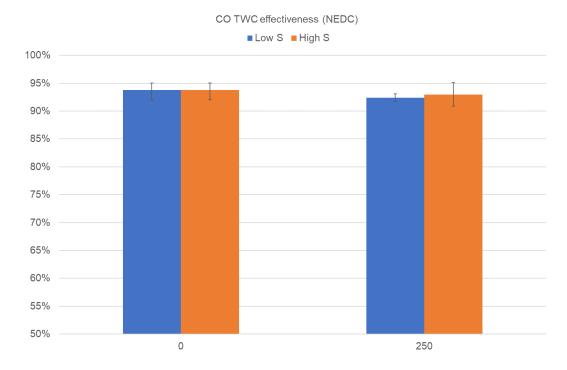


Figure 46 TWC conversion efficiency calculated from CO emissions results for both test objects, tested over the entire NEDC.



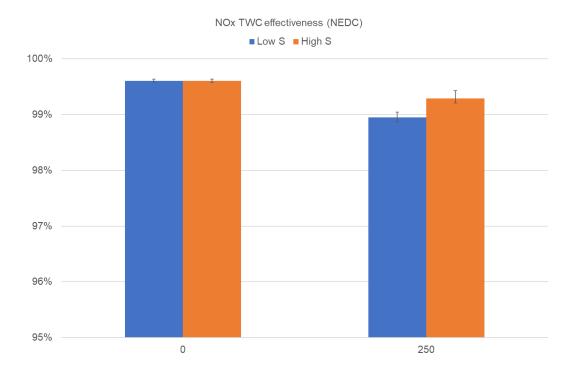
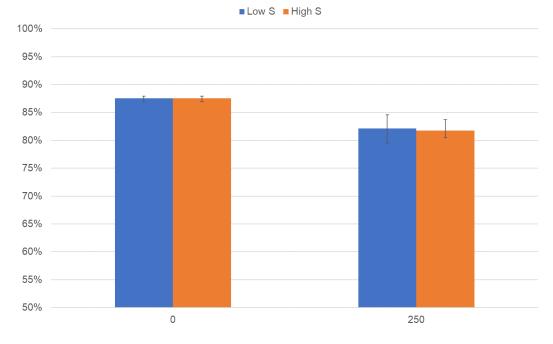


Figure 47 TWC conversion efficiency calculated from NO_x emissions results for both test objects, tested over the entire NEDC.

Essentially the same trends were observed over the UDC phase of the NEDC, as shown in Figures 48-51. Conversion efficiency fell at 250 cycles, but with very good agreement for the two test objects in the case of THC, NMHC and CO, although the decrease for CO was small. In the case of NO_x , conversion efficiency also fell, but at 250 cycles the High S TWC outperformed its counterpart by a margin which may have been significant.





THC TWC effectiveness (NEDC-UDC)



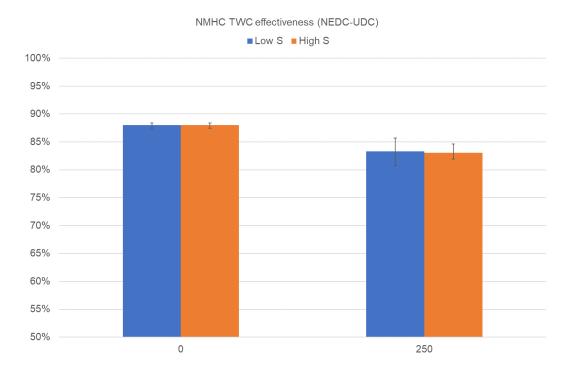
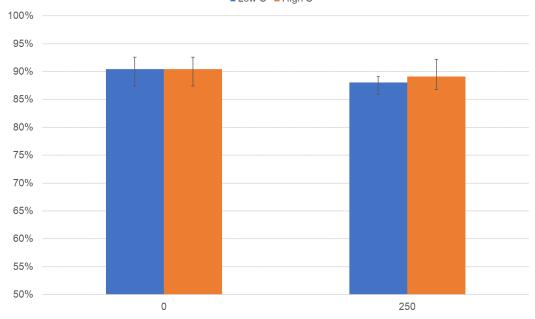


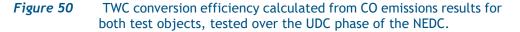
Figure 49 TWC conversion efficiency calculated from NMHC emissions results for both test objects, tested over the UDC phase of the NEDC.

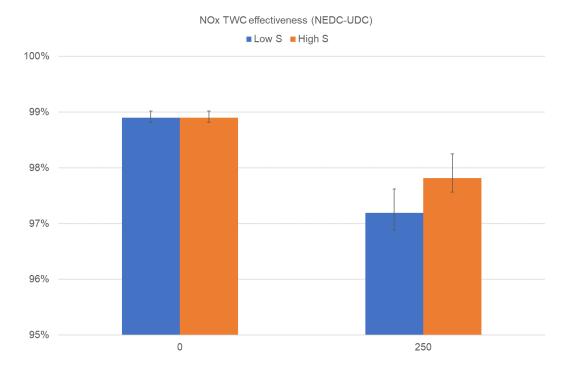




CO TWC effectiveness (NEDC-UDC)

Low S High S







As shown in Figures 52-55, TWC conversion efficiency over the constant speed cycle was very high in all cases, since the cycle was performed with a fully warmed up powertrain and at constant speed - i.e. under vehicle operating conditions



which facilitate very stable engine operation (as well as low distance-specific fuel consumption). When driving at a constant speed of 80 km/h, there is no inertia to overcome and the power absorbed by the chassis dyno for the test vehicle was 5 kW, i.e. 5.7% of the rated power of the engine. Under such conditions, TWC performance was consistently very high, even after 250 ageing cycles. For both TWCs, at the 0 and 250 cycle stages, calculated TWC conversion efficiency did not fall below 98.4% for any of the measured gaseous compounds.

In the case of THC and NMHC, conversion efficiency was very close to 100% for both test objects at both stages. Slightly lower CO conversion efficiency of the High S TWC was observed, but this effect was also present at 0 cycles, i.e. before any ageing had been carried out. Nevertheless, the CO conversion efficiency for High S at 250 cycles was noticeably lower than at 0 cycles.

THC TWC effectiveness (Constant speed - 80 km/h in 5th gear)

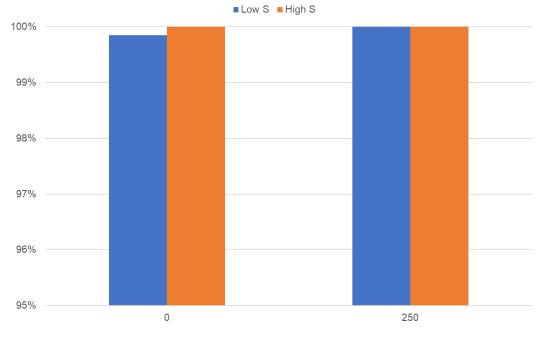
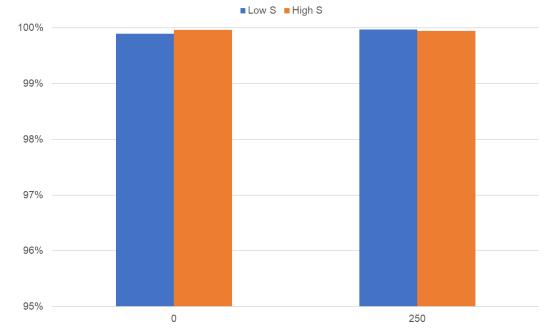


Figure 52 TWC conversion efficiency calculated from THC emissions results for TWC Low S, tested over the constant speed cycle.

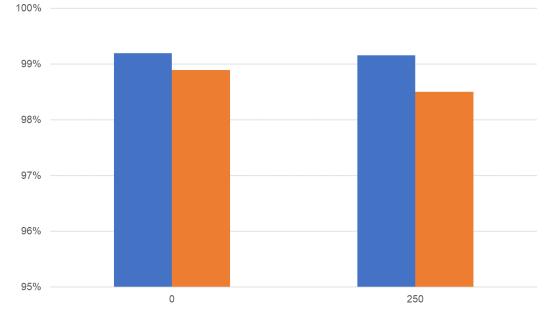


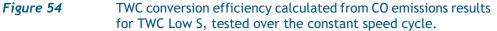


NMHC TWC effectiveness (Constant speed - 80 km/h in 5th gear)



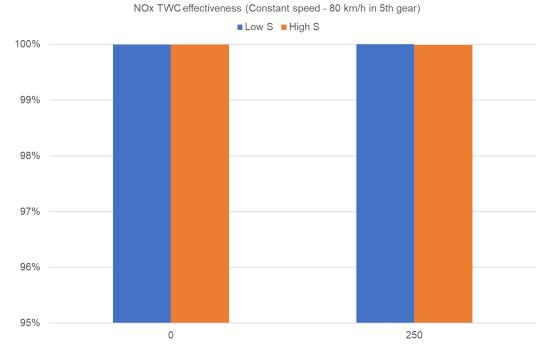
CO TWC effectiveness (Constant speed - 80 km/h in 5th gear)
Low S High S







As regards NO_x , the conversion efficiency was at a very high level for both test objects at both ageing stages and there only negligible differences following ageing. The very low magnitude of the differences and the fact that two repeat tests were performed (n=2) means no statistically significant differences were observed at regards NO_x elimination over the constant speed cycle.





TWC conversion efficiency calculated from NO_x emissions results for TWC Low S, tested over the constant speed cycle.

4.2.3. Results of ECU parameter recordings

ECU parameters were logged for all emissions tests. Parameters such as engine speed, engine coolant temperature, etc showed high stability, with very limited test-to-test variations.

The temperature of the exhaust gas reported by the vehicle's ECU was recorded during emissions tests. As mentioned previously, the test vehicle did not feature a thermocouple and the reported temperature of the exhaust gas was a modelled parameter, designed to reflect the temperature of the exhaust gas upstream of the aftertreatment (TWC). This parameter is of critical importance for the functioning of the TWC for a cold start driving cycle. While the temperature traces were subject to slight variations from test to test, generally the temperature traces over the WLTC for four selected WLTC tests (two on each test object), while Figures 58 and 59 show the temperature traces over the NEDC for four selected NEDC tests (two on each test object). Lines of different thickness have been used in the plots to allow both curves to be seen, as differences are generally very limited.



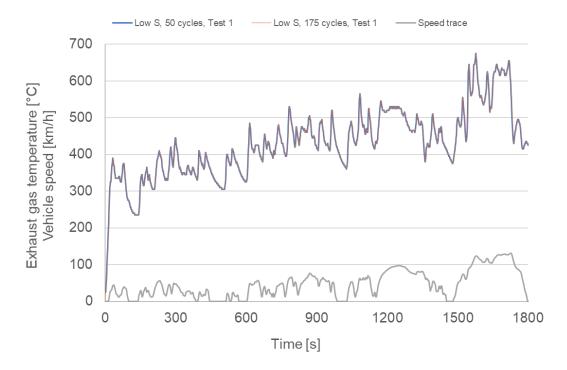
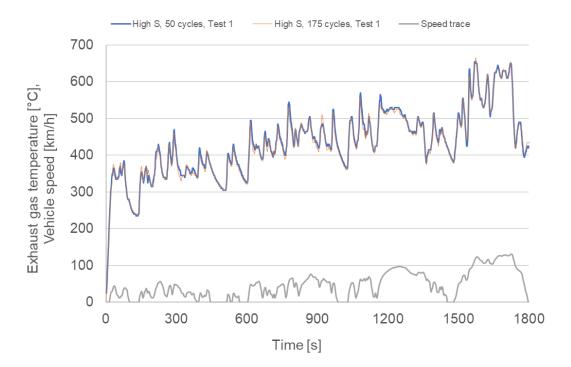


Figure 56 Two sample temperature traces (measured ECU parameter 'Exhaust gas temperature') for TWC Low S during WLTC emissions tests.





Two sample temperature traces (measured ECU parameter 'Exhaust gas temperature') for TWC High S during WLTC emissions tests.



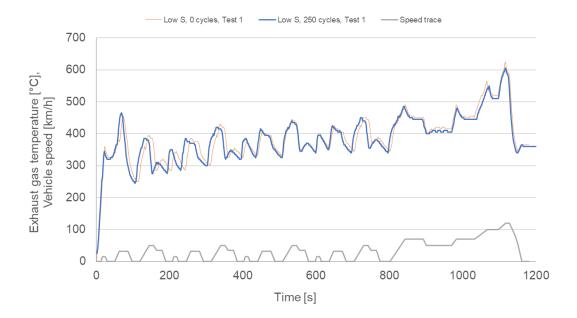


Fig. 58 Two sample temperature traces (measured ECU parameter 'Exhaust gas temperature') for TWC Low S during NEDC emissions tests.

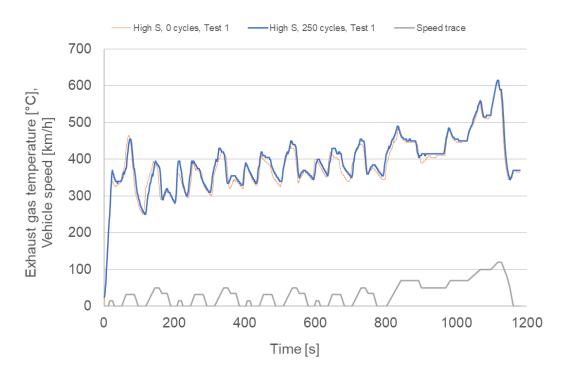


Figure 59 Two sample temperature traces (measured ECU parameter 'Exhaust gas temperature') for TWC High S during NEDC emissions tests.

In all cases, the initial increase in temperature from ambient to a value of approximately 350° C showed very little variation from test to test, and was in fact similar for both test cycles employed (WLTC, NEDC). As shown in Figures 56 and 57, for the majority of the WLTC the temperature oscillated between approximately 300° C and 550° C, rising to higher values during the final 300



seconds of the cycle (essentially corresponding to the Extra High phase of the WLTC). For the NEDC (Figures 58 and 59), for the majority of the cycle the temperature oscillated between approximately 300° C and 500° C, rising to higher values above 500° C only during the final portion of the cycle (where vehicle speed is $\geq 100 \text{ km/h}$). For constant speed testing, the temperature of the exhaust gas quickly stabilised at a value of approximately 470° C to 475° C during the early phases of the warmup period before emissions sampling commenced. During the emissions measurement phases themselves, there were very limited fluctuations outside the range $470-475^{\circ}$ C.

As mentioned previously (shown in Figure 4 and discussed in [10]), under most engine operating conditions the temperature of the TWC monolith was likely to be noticeably higher than the reported temperature of the exhaust gas. Thus, the temperatures shown in Figures 56-59 can be treated as minimum likely TWC monolith temperatures, with the exception of the first 30 seconds or so immediately following cold start, during which the temperature of the monolith is lower than that of the exhaust gas.



5. CONCLUSIONS

Ageing equivalent to 71 thousand km of vehicle usage was carried out on two TWCs, each being aged on its own LPG fuel type, with the only significant difference between the two fuel types being the sulphur level. The fuels' sulphur levels were 8.2 ppm ('Low S') and 29.0 ppm ('High S').

The variability in the results of periodic emissions testing was deemed acceptable and typical for measurements of this type performed on such a test vehicle over cold start driving cycles. Variability was, generally speaking, greater at higher ageing stages (though not in all cases), which would be consistent with the theory that the TWC's conversion efficiency became increasingly sensitive to λ control as ageing progressed and oxygen storage capacity became compromised (lost, temporarily reduced or inhibited in terms of chemical kinetics).

With a single exception, the test vehicle met the applicable Euro 6 emissions limits when tested using its type approval procedure (NEDC), for both TWCs, at all ageing stages. The exception to this came in the form of a single NMHC emissions result, which in one test was found to be above the applicable legislative limit following 250 ageing cycles; the two other repetitions of this test under the same conditions showed NMHC emissions below with the Euro 6 limits, and the mean of these 3 tests was also below the Euro 6 limits. While emissions results obtained using the WLTP test procedure were not legally applicable to the test vehicle, results obtained using that procedure were also below the Euro 6 limits, in all cases, with no exceptions.

Despite being type approved at the Euro 6b level (for which the NEDC test is legally applicable), the test vehicle showed low emissions over the WLTC, with none of the results for either of the test objects (TWCs) obtained from that test type exceeding the Euro 6 limits at any ageing stage. As is well known, the relatively long distance covered by the WLTC (over 23 km - i.e. more than twice the 11 km distance covered by the NEDC) leads to a reduction in the impact of the cold start effect, which causes emissions associated with cold start to be subject to a low distance-specific weighting.

The test vehicle proved itself to be stable. No vehicle malfunctions or ECU errors were present before, during or after any emissions test and the vehicle MIL lamp did not illuminate at any point. Carbon dioxide emissions and fuel consumption results were generally stable throughout the test programme.

The relatively low emissions results occurring even after extended ageing indicate high TWC conversion efficiency and durability under the specific ageing conditions employed here. There was an overall tendency for emissions to slightly increase as the number of ageing cycles increased, but trends were not monotonic in all cases. As regards the impact of fuel sulphur level on TWC conversion efficiency, overall there appeared to be no significant difference between the two test objects. In certain cases, differences in performance were apparent but sometimes the High S TWC outperformed its Low S counterpart. This suggests that the thermal degradation induced by the ageing procedure was more relevant to the performance of the TWCs tested in this study than the fuel sulphur level. A possible explanation offered for this is that the temperatures achieved during the ageing procedure permitted periodic desulphation of the test objects [6-9], meaning that the long-term impact of the sulphur present in the LPG fuel on TWC performance was low. When evaluating the impact of the ageing performed on the test objects, it is important to underline that a real engine, running under



demanding real world operating conditions was used. The ageing cycle featured multiple periods of elevated temperature and generally high mean temperatures (as presented in Section 3 and specifically Figure 3), but, as shown in Figure 4, such temperatures can also be reached during normal, real-world driving at speeds >100 km/h, even without additional load (i.e. uphill gradient and/or high vehicle payload). As a single WLTC preconditioning cycle was carried out prior to every batch of emissions tests, there was some further exposure to elevated temperatures prior to the emissions tests, as well as during the emissions tests themselves (as shown in Figures 56 and 57). Results in this study showed no overall trend of TWC conversion efficiency increasing from test to test within a given test batch (as might be expected if the TWC were being gradually purged of sulphur and thereby progressively recovering its conversion efficiency).

Notwithstanding the small differences observed over the test cycles employed, there was a more visible tendency for ageing to increase emissions over the cold start phases of the two tests (WLTC Low, NEDC UDC). This period is characterised by generally high engine out emissions and low TWC conversion efficiency (mainly due to the thermal state of the monolith following cold start). Differences in emissions and TWC conversion efficiency were of somewhat greater magnitude for WLTC Low and NEDC UDC. Nevertheless, focusing on the results obtained from the aforementioned cold start phases, no consistent, significant difference between the two test objects could be observed. This supports the observation that the ageing procedure indeed reduced TWC performance, but that fuel sulphur level had no measurable overall impact. Under high load conditions, the TWC's temperature is well in excess of its light-off point. The conversion efficiency of both test objects for the WLTC High and Extra High phases decreased only very slightly (or not at all) as the two test objects were aged from 0 to 250 cycles. Comparing results at 0 and 250 cycles for the EUDC phase of the NEDC, reductions in conversion efficiency were of similar magnitude. Thus, when operating under conditions which were predominantly high load and which featured high exhaust gas temperatures, the ability of the test objects to perform their intended function showed very low sensitivity to ageing and exposure to sulphur.

As should be expected, there was excellent agreement between the results obtained from both TWCs at the 0 cycle stage. For both TWCs, the WLTC and NEDC results at the 250 cycle stage showed a deterioration compared to the 0 cycle stage - i.e. TWC conversion efficiency was lower and exhaust emissions were higher. For interim stages (50, 100, 175 cycles), trends were not always monotonic - some results showed higher TWC conversion performance at 175 cycles than at 100 cycles, although the magnitude of the uncertainty associated with the mean of the emissions results (n=3) should be kept in mind. A further point to mention is that the conversion of the High S TWC performed better than the Low S TWC at certain ageing stages and for certain compounds. Taking into account the spread of the results, quantified as the difference between the lowest and highest measured results, as well as the type A uncertainty, such differences are again unlikely to be statistically significant. Nevertheless, the fact remains that in some cases ageing on higher sulphur content LPG was associated with lower measured tailpipe emissions of regulated compounds, as well as higher TWC conversion efficiency.

Over the transient cold start driving cycles (NEDC, WLTC), TWC conversion efficiency was observed to fall somewhat as the test objects were subjected to ageing. However, during the constant speed tests, the TWC conversion efficiency at the 250 cycle stage was very close to that at the 0 cycle stage. Thus, there was no significant deterioration for either test object under these conditions. At temperatures well above the test units' light-off temperature and at stable λ , the



performance (i.e. elimination of THC, NMHC, CO and NO_x) remained very high, even following extensive ageing on high sulphur fuel. This finding would appear to support the hypothesis that ageing primarily affected the performance temperature of the test objects at low temperatures. As a result of this, the dynamic cold start test procedures (NEDC, WLTC) revealed some deterioration in TWC performance, while the steady-state, thermally stabilised testing did not reveal such effects.

As it was assumed that the low sensitivity of the TWC conversion efficiency was related to a desulphatation process occurring at higher equivalence ratio and high temperature, a complementary study was performed to challenge this assumption (details in the appendix). It consisted in chemical analyses of the aged TWCs, using advanced laboratory methods. Unfortunately, this study remained inconclusive, as it were unable to directly link the sulphur level measured in the TWCs to their conversion efficiency loss. Consequently, lacking a clear and systematic explanation about the effect of sulphur on the TWC conversion efficiency, this study cannot be 100% conclusive regarding the harmful/non-harmful effect of sulphur content in LPG on the TWC conversion efficiency, even if the engine/vehicle tests tend to show that a higher sulphur content is not harmful.



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APPENDIX - DETAILED EXHAUST EMISSIONS RESULTS

Table 7 Emissions and fuel consumption results from the Fiat Tipo 1.4 vehicle over the NEDC cycle for TWC Low S

| BOS | | ve RåD Institu | ALC
otry | | | |
 | | |

 |

 | | |
 | NEDC 1 | test (UNE | CE R83
 |) - NEDC | driving c | ycle | |
 | | | |
 | | | | |
|---------------------|------------------------------|---|-------------|--|---|--
--|---|---
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--	--	---	---
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VIN: ZFA:	5600006K20	0252	
 | Vehicle | e model: | Fiat Tip

 | o 1.4 LP

 | G | |
 | | | En
 | lission s | andard: I | Euro 6 | |
 | | Ту | res: | Continent
 | al ContiEco | Contact 5 2 | 225/45 R17 | V XL |
| Inertia [kg | 1360 | | | | | | Emis
 | sions in | the NED | C test

 |

 | | |
 | Emission | is in the UD | C phase
 | | | Emission | s in the EU | DC phase
 | | C | CO ₂ emissio | ons
 | Fu | el consump | notion | | | | |
| Mieane | | Chassis | | | missions velo | |
 | | |

 | na measured

 | | | | |
 | | issions measu |
 | | | | isalona mesau |
 | | | [g/km] | ,
 | | [l/100 km] (** |) | Note 1 |
| [km] | Date | dyno
F0/F1/F2 | Test No. | THC | NMHC | CO
a/km] | NOx
 | THC | NMHC | CO

 | NOx

 | PM | PN | THC
 | NMHC | CO
[ma/km] | NUX
 | PN | THC | NMHC | CO
[ma/km] | NUX
 | PN | NEDC | UDC | EUDC
 | NEDC | UDC | EUDC | | | | |
| Ageing sta | ge: 0 cycles | | | BAG - MOD | AL DIL - PI | |
 | | |

 |

 | | | | |
 | | |
 | | | | |
 | | | |
 | | | | |
| | | 21.0 | | 73 | 66 | 846 | 15
 | 56
57 | 51
52 | 564

 | 10

 | 0.54 | 4.32E+11 | 151
 | 137
140 | 1449
1433 | 22
 | 1.14E+12 | 0 | 0 | 46
48 | 2
 | 1.57E+10 | 161.4
161.9 | 223.1
223.0 | 125.3
 | 9.99 | 13.89
13.88 | 7.71 | Bags
Modal Dil |
| 4 061 | 27.09.2018 | 0.0401 | L1-0435 | | | |
 | 702 | 667 | 7054

 | 2376

 | | | 1149
 | 1087 | 1433 | 1875
 | | 441 | 421 | 4434 | 2669
 | | 153.4 | 223.0 | 120.1
 | 10.02 | 13.66 | 7.90 | Modal PRE ca |
| | | | | Í | | 1 |
 | 70 | 63 | 601

 | 11

 | - | | 188
 | 169 | 1528 | 26
 | 1.1 | 0 | 0 | 59 | 2
 | - | 165.1 | 227.4 | 128.7
 | 10.22 | 14.17 | 7.92 | Modal TP |
| | | | | | | | ess (pre-bag)
Iss (pre-post)
 | 92.1%
90.1% | |

 |

 | | | 86.9%
 | 87.4%
84.4% | 87.4% | 98.8%
 | | 99.9% | 99.9% | 99.0% | 99.9%
99.9%
 | | | |
 | | | | TWC eff
TWC eff |
| | | 21.0 | | 63 | 57 | 634 | 14
 | 48 | 44 | 423

 | 9

 | 0.67 | 4.34E+11 | 131
 | 119 | 1059 | 18
 | 1.13E+12 | 0 | 0 | 50 | 3
 | 2.41E+10 | 161.9 | 221.9 | 126.8
 | 10.01 | 13.77 | 7.80 | Bags |
| 4 083 | 03.10.2018 | -1.13 | L1-0437 | | | |
 | 49
675 | 45 | 423

 | 8
2354

 | | | 134
1065
 | 122 | 1056 | 18
1865
 | | 0 445 | 0
426 | 52
4547 | 3
2640
 | | 162.4 | 222.3 | 127.4
 | 10.04 | 13.80 | 7.84 | Modal Dil
Modal PRE ca |
| | | 0.0401 | | | | |
 | 58 | 53 | 449

 | 2354

 | - | | 1065
 | 142 | 12085 | 22
 | - | 445 | 426 | 4547
62 | 2640
 | - | 165.6 | 208.4 | 120.9
 | 10.25 | 14.18 | 8.00 | Modal PRE Ca
Modal TP |
| | | | | | | | ess (pre-bag)
 | 92.8% | 93.1% | 94.29

 |

 | | | 87.7%
 | 88.2% | 91.2% | 99.0%
 | 1.1 | 100.0% | 100.0% | 98.9% | 99.9%
 | | | |
 | | | | TWC eff |
| | | 21.0 | | 61 | TWC 6 | fectivene:
522 | iss (pre-post)
 | 91.4%
47 | 91.8%
43 | 93.9 ⁵
348

 | 6 99.65
10

 | 0.29 | 2.93E+11 | 85.3%
128
 | 86.0% | 90.8%
858 | 98.8%
 | 7.675+14 | 100.0% | 99.9% | 98.6%
52 | 99.9%
 | 1055+10 | 160.5 | 223.0 | 124.3
 | 9.91 | 13.82 | 7.65 | TWC eff
Bags |
| 4 209 | 40.40.00.0 | -1.13 | L1-0450 | 01 | 00 | 522 | 15
 | 4/ | 43 | 348

 | 10

 | 0.29 | 2.900+11 | 128
 | 11/ | 858 | 20
 | - | 0 | 0 | 54 | 4
 | | 160.5 | 223.0 | 124.3
 | 9.91 | 13.82 | 7.65 | Modal Di |
| 4 209 | 16.10.2018 | 0.0401 | L1-0450 | | | |
 | 648 | 617 | 7044

 | 2309

 | - | - | 1058
 | 1005 | 11622 | 1767
 | | 411 | 393 | 4396 | 2623
 | | 151.9 | 208.8 | 119.0
 | 10.14 | 14.16 | 7.82 | Modal PRE ca |
| | | 1 | 1 | <u> </u> | TWC | effectivene | ess (pre-bag)
 | 52
92.7% | 48 | 353

 | 11

 | - | 1 | 143
87.9%
 | 130 | 854
92.6% | 23
98.9%
 | | 0 | 0 | 63
98.8% | 4 99.9%
 | - | 164.1 | 227.5 | 127.5
 | 10.14 | 14.10 | 7.85 | Modal TP
TWC eff |
| | | | | | | | iss (pre-post)
 | | 92.3% | 95.07

 |

 | | - | 86.5%
 | 87.1% | 92.8% | 98.7%
 | | 100.0% | 99.9% | | 99.9%
 | | 1 | | | | | |
 | | | | TWC eff |
| | | | | | | |
 | 50
52 | 46 | 445

 | 9

 | 0.50 | 3.87E+11 | 136
139
 | 124 | 1122
1114 | 20
 | 1.02E+12 | 0 | 0 | 50
51 | 3
 | 1.97E+10 | 161.3
161.8 | 222.7 | 125.5
 | 9.97
10.00 | 13.83
13.84 | 7.72 | Bags
Modal Dil |
| | | | | | Mean | values |
 | 675 | 642 | 7143

 | 2346

 | | | 139
 | 127 | 1114 | 1835
 | | 433 | 413 | 51
4459 | 3
 | | 161.8 | 209.2 | 126.2
 | 10.00 | 13.84 | 7.76 | Modal DI
Modal PRE ca |
| | | | | | | |
 | 60 | 54 | 468

 | 11

 | · · | | 162
 | 147 | 1164 | 23
 | | 0 | 0 | 61 | 3
 | | 164.9 | 227.2 | 128.7
 | 10.20 | 14.11 | 7.92 | Modal TP |
| | | | | | | |
 | 3.9
4.2 | 3.4 | 89.7
87.8

 | 0.5

 | 0.16 | 6.59E+10 | 10.2
 | 8.9
9.7 | 245.2
240.0 | 1.6
 | 1.76E+11 | 0.1 | 0.1 | 2.5 | 0.5
 | 3.43E+09 | 0.58 | 0.55 | 1.01
 | 0.04 | 0.05 | 0.06 | Bags
Modal Dil |
| | | | | | Standard | deviation | n
 | 4.2 | 20.2 | 132.6

 | 27.8

 | | | 41.3
 | 37.5 | 240.0 | 48.7
 | | 15.5 | 14.5 | 64.1 | 19.0
 | | 0.66 | 0.39 | 0.95
 | 0.04 | 0.03 | 0.06 | Modal Dil
Modal PRE ca |
| | | | | | | |
 | 7.2 | 6.3 | 102.2

 | 0.5

 | | | 19.2
 | 16.7 | 277.9 | 1.5
 | | 0.0 | 0.0 | 1.9 | 0.6
 | | 0.62 | 0.37 | 0.99
 | 0.04 | 0.04 | 0.06 | Modal TP |
| | | | | | | |
 | 2.2 | 2.0 | 51.8
50.7

 | 0.3

 | 0.09 | 3.80E+10 | 5.9
6.5
 | 5.1
5.6 | 141.6
138.5 | 0.9
 | 1.01E+11 | 0.1 | 0.1 | 1.5 | 0.3
 | 1.98E+09 | 0.34 | 0.32 | 0.58
 | 0.02 | 0.03 | 0.04 | Bags
Modal Dil |
| | | | | | Type A u | ncertainty | v
 | 12.8 | 11.7 | 76.5

 | 16.0

 | - | - | 23.9
 | 21.7 | 139.5 | 28.1
 | | 8.9 | 8.4 | 37.0 | 11.0
 | | 0.38 | 0.49 | 0.44
 | 0.03 | 0.03 | 0.03 | Modal PRE ca |
| | | | | | | |
 | 42 | 3.6 | 59.0

 | 0.3

 | | | | | | | |
 | | |
 | | | | |
 | | | |
 | | 0.02 | | |
| | | | | | | |
 | | |

 |

 | | | 11.1
 | 9.6 | 160.5 | 0.9
 | | 0.0 | 0.0 | 1.1 | 0.3
 | | 0.36 | 0.22 | 0.57
 | 0.03 | 0.02 | 0.03 | Modal TP |
| | | | | | TWC effect | |
 | 92.6% | 92.9% | 93.87

 | 6 99.63

 | | - | 11.1
87.5%
87.9%
 | 9.6
88.0%
88.4% | 160.5
90.4%
92.6% | 0.9
98.9%
99.0%
 | | 0.0
99.9%
100.0% | 0.0
99.9%
100.0% | 1.1
98.9%
99.0% | 0.3
99.9%
99.9%
 | | 0.36 | 0.22 | 0.57
 | 0.03 | 0.02 | 0.03 | Modal TP |
| | | | | Max. T
Min. T | WC effect
WC effect | tiveness (p
tiveness (p | pre-bag)
pre-bag)
 | 92.6%
92.8%
92.1% | 92.9%
93.1%
92.4% | 93.87
95.17
92.07

 | 6 99.61
6 99.61
6 99.61

 | 6 -
6 - | | 87.5%
87.9%
86.9%
 | 88.0%
88.4%
87.4% | 90.4%
92.6%
87.4% | 98.9%
99.0%
98.8%
 | - | 99.9%
100.0%
99.9% | 99.9%
100.0%
99.9% | 98.9%
99.0%
98.8% | 99.9%
99.9%
99.9%
 | - | 0.36 | 0.22 | 0.57
 | 0.03 | 0.02 | 0.03 | Modal TP |
| | | | | Max. T
Min. T
Mean T | WC effect
WC effect | tiveness (p
tiveness (p
tiveness (p | pre-bag)
pre-bag)
pre-post)
 | 92.6%
92.8%
92.1%
91.1% | 92.9%
93.1%
92.4%
91.6% | 93.87
95.17
92.07
93.47

 | 6 99.63
6 99.63
6 99.63
6 99.63

 | 6 -
6 -
6 - | - | 87.5%
87.9%
86.9%
85.1%
 | 88.0%
88.4%
87.4%
85.8% | 90.4%
92.6%
87.4%
90.1% | 98.9%
99.0%
98.8%
98.7%
 | • | 99.9%
100.0%
99.9%
100.0% | 99.9%
100.0%
99.9%
99.9% | 98.9%
99.0%
98.8%
98.6% | 99.9%
99.9%
99.9%
99.9%
 | - | 0.36 | 0.22 | 0.57
 | 0.03 | 0.02 | 0.03 | Modal TP |
| | | | | Max. T
Min. T
Mean T
Max. T
Min. T | WC effect
WC effect
WC effect
WC effect
WC effect | tiveness (p
tiveness (p
tiveness (p
tiveness (p | pre-bag)
pre-bag)
pre-post)
pre-post)
 | 92.6%
92.8%
92.1% | 92.9%
93.1%
92.4%
91.6%
92.3% | 93.87
95.17
92.07
93.47
93.47

 | 6 99.61
6 99.61
6 99.61
6 99.61
6 99.61

 | 6 -
6 -
6 - | | 87.5%
87.9%
86.9%
 | 88.0%
88.4%
87.4% | 90.4%
92.6%
87.4%
90.1%
92.7% | 98.9%
99.0%
98.8%
 | •
•
•
• | 99.9%
100.0%
99.9% | 99.9%
100.0%
99.9% | 98.9%
99.0%
98.8%
98.6%
98.7% | 99.9%
99.9%
99.9%
 | - | 0.36 | 0.22 | 0.57
 | 0.03 | 0.02 | 0.03 | Modal TP |
| Ageing sta | ge: 250 cycles | | | Max. T
Min. T
Mean T
Max. T | WC effect
WC effect
WC effect
WC effect
WC effect | tiveness (p
tiveness (p
tiveness (p
tiveness (p | pre-bag)
pre-bag)
pre-post)
pre-post)
 | 92.6%
92.8%
92.1%
91.1%
91.9%
90.1% | 92.9%
93.1%
92.4%
91.6%
92.3%
90.6% | 93.87
95.17
92.07
93.47
93.47
95.07
91.57

 | 6 99.63
6 99.63
6 99.63
6 99.63
6 99.63
6 99.63

 | 6 -
6 -
6 -
6 - | - | 87.5%
87.9%
86.9%
85.1%
86.5%
83.6%
 | 88.0%
88.4%
87.4%
85.8%
87.1%
84.4% | 90.4%
92.6%
87.4%
90.1%
92.7%
86.8% | 98.9%
99.0%
98.8%
98.7%
98.8%
98.8%
 | -
-
-
-
- | 99.9%
100.0%
99.9%
100.0% | 99.9%
100.0%
99.9%
99.9% | 98.9%
99.0%
98.8%
98.6%
98.7%
98.6% | 99.9%
99.9%
99.9%
99.9%
99.9%
99.9%
 | - | | |
 | | | | |
| | | 21.0 | | Max. T
Min. T
Mean T
Max. T
Min. T | WC effect
WC effect
WC effect
WC effect
WC effect | tiveness (p
tiveness (p
tiveness (p
tiveness (p | pre-bag)
pre-bag)
pre-post)
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 THC
 NMHC
 CO
 NOx

 Euro 6 SI limits [mg/km]
 100
 68
 1000
 60

(*) - as defined in Regulation (EC) 2007/595, applied only at the 0 cycle ageing stage (for informational purposes)



Table 8Emissions and fuel consumption results from the Fiat Tipo 1.4 vehicle over the WLTCcycle for TWC Low S at 0 cycles

	Automotive Rese Exhaust Emissi		opment	Institute Ltd																WL	TP test	Reg 2	017/11	51) - WL	LTC dr	iving c	cycle				I										
VIN: ZFA356	600006K20252	2			Vehi	cle mo	del:					I	Fiat Tip	00 1.4 LI	PG						E	mission	standard	Euro 6								Ty	res:			Contine	ntal ContiEcoC	iontact 5 225/4	5 R17 V XL		
Inertia [kg]:		1509				E	mission W	LTC						ision LOW				Emission					Emission HI	3H			En	nission Ex-H	IGH			(CO ₂ emissio	n			Fr	uel consum	ption		_
Mileage[km]	Date	Chassis dyno F0/F1/F2	Test N	b. THC	NMHC	c	[mg/km]	NOx	PM	PN	THC	N	INC I	mg/km] CO	NOx PN	THC	NMHC	[mg/l		NOX PN	THC	NMHC	[mg/km] CO	NOx	PN	THC	NMHC	[mg/km] CO	NOx	PN	WLTC	LOW	(g/km) MIDDLE	HIGH	Ex-HIGH	WLTC	LOW	[l/100 km] ^G	HIGH	Ex-HIGH	Note 1
Ageing stage	: 0 cycles			BAG - MC	DAL DIL - PR			. 1				-					1		<u> </u>			1	1						1	_		1	1		1		<u> </u>	1	1		
d stude		45.1		57	53			26	1.21	6.17E+11	426	3	94	2229	36 4.19E+12	0	0	18	81	4 1.37E+	11 0	0	128	5	2.82E+10	1	1	90	54	6.54E+10	148.6	215.7	145.1	128.7	142.7	9.19	13.56	8.94	7.93	8.78	Bags
		-0.87		59	55	40	10	26	-		442	4	09	2198	35 -	1	0	18	11	4 -	0	0	128	5		1	1	89	53	-	149.1	216.3	144.9	128.6	144.1	9.22	13.60	8.93	7.92	8.87	Modal Dil
4 094	2018-10-04	0.0390	L1-043	38 717	687	69	92 2	473	-		1665	15	594	13826	1390 -	778	748	835	54	1812 -	568	545	5706	2272	-	458	436	4769	3432	-	139.0	199.9	129.4	119.3	138.8	9.36	13.94	8.91	7.99	9.08	Modal PRE cat
				65	60	42	24	27	-	-	490	4	51	2234	42 -	0	0	19	10	5 -	0	0	151	4	-	0	1	120	54	-	152.1	220.7	147.8	131.2	147.0	9.41	13.88	9.11	8.08	9.05	Modal TP
	TWO	C effectivenes	s (pre-b	ag) 92.1	% 92.3	% 9	4.2%	98.9%			74.4	%	75.3%	83.9%	97.4% -	100.05	6 100.	.0% 9	7.8%	99.8% -	100.0%	100.05	6 97.8%	99.8%		99.9%	99.9%	98.1%	98.4	% -											TWC eff
	TWC	C effectiveness	(pre-pc	ost) 90.9	% 91.2	K 9	3.9%	98.9%	-	-	70.6	%	71.7%	83.8%	97.0% -	100.05	6 99.	9% 9	7.7%	99.8% -	100.0%	100.05	6 97.4%	99.8%	-	99.9%	99.9%	97.5%	98.4	% -											TWC eff
	4	45.1		47	43	5	15	10	1.02	6.01E+11	353	3	23	2315	40 4.11E+12	1	0	32	27	3 4.27E	10 0	0	428	6	8.40E+09	1	1	25	8	1.22E+11	150.1	218.8	146.9	129.1	144.4	9.29	13.75	9.07	7.98	8.88	Bags
4 117	2018-10-09	-0.87	L1-044	50	45	51		10			367			2303	36 -	1	1	32		3 -	1	1	420	6	•	1	1	26	7	-	150.8	219.2	146.9	129.3	146.0	9.33	13.77	9.06	7.99	8.98	Modal Dil
4	2010-10-05	0.0390	21.04	700	669	76		436	-	-	1573			15241	1314 -	759	726			1836 -	584	560	6597	2152	· .	442	421	4531	3444	-	139.7	201.4	130.6	118.2	140.4	9.46	14.15	9.10	8.02	9.16	Modal PRE cat
				56	51	5		11			417			2240	43 -	1	1	33		3 -	0	0	441	5		0	1	35	9	1.1	153.8	223.6	149.7	131.9	148.9	9.52	14.04	9.24	8.15	9.16	Modal TP
		C effectivenes						99.6%		-	77.5		78.5%	84.8%	97.0% -	99.95			6.6%	99.9% -	99.9%					99.9%															TWC eff
	TWC	C effectiveness	(pre-pc					99.6%			73.5		74.7%	85.3%	96.7% -	99.95			6.4%	99.9% -	100.0%					99.9%															TWC eff
	4	45.1		43	39		-	11	0.68	5.32E+11	317		89	2284	49 3.65E+12	1	0		89	10 5.47E		0	109		1.51E+10	1	1	46	3	8.98E+10	151.7	222.6	147.3	130.5	146.3	9.38	13.97	9.07	8.04	9.00	Bags
4 131		-0.87	L1-045	58 44	40			10	-	-	330		00	2287	46 -	1	1	19		10 -	1	0	111	4	•	1	0	46	3		152.5	224.1	147.2	130.9	147.6	9.43	14.07	9.07	8.06	9.08	Modal Dil
	() ()	0.0390		592	563	68		534	-	-	1318			13600	1457 -	613				1911 -	468	446	5676	2317	-	417	396	4848	3483		144.2	211.1	135.0	122.7	143.0	9.64	14.54	9.15	8.18	9.34	Modal PRE cat
				49	45			11		1.1	371		36	2285	52 -	0	0	20		10 -	0	0	112	4		0	0	57	4	-	155.5	228.5	150.0	133.4	150.6	9.61	14.34	9.24	8.22	9.27	Modal TP
		C effectivenes						99.6%		-	75.9		76.9%	83.2%	96.6% -	99.95			7.5%	99.5% -	99.9%					99.9%															TWC eff
	TWC	C effectiveness	(pre-pc	ost) 91.7	% 92.0 45			99.5% 16		5.83E+11	71.9		73.1%	83.2% 2276	96.4% - 42 3.99E+12	99.95			7.3%	99.5% - 6 7.82E*	100.0%	99.99	6 98.0% 222			100.0%	99.9%	98.8%			450.4	219.0	146.4	129.4		9.28	13.76	9.03	7.00	0.00	TWC eff
				49	45			15	0.97	5.63E+11	366		35	2263	42 3.99E+12 39 -	1				6 7.82E+	10 0	0	222	5	1.72E+10	1	1	54	22	9.24E+10	150.1 150.8	219.0	146.3	129.4	144.4	9.20	13.76	9.03	7.90	8.89	Bags Modal Dil
	Mean va	ralues		670	640	71		481			1519			14222	1387 -	717				1853 -	540	517	5993	2247		439	418	4716	3453		140.9	204.1	140.3	129.6	140.7	9.32	14.21	9.02	8.06	9.19	Modal PRE cat
				57	52	_		16			426			2253	46 -	0				6 -	0	0	235	4		435	1	70	22		153.8	224.3	149.2	132.2	148.8	9.51	14.09	9.20	8.15	9.16	Modal TP
				5.9	5.8	55		7.4	0.22	3.68E+10	44.9		3.7	35.4	5.4 2.40E+11	0.2				3.3 4.21E4		0.1	145.9		8.21E+09	0.0	0.0	27.0	23.0	2.32E+10	1.30	2.80	0.94	0.78	1.48	0.08	0.17	0.06	0.04	0.09	Bags
				6.1	6.1			7.4		-	46.5		5.4	46.4	5.0 -	0.2				3.1 -	0.1	0.2	141.5	0.7		0.0	0.1	26.4	22.7	-	1.40	3.20	1.00	0.93	1.45	0.08	0.19	0.06	0.06	0.09	Model Dil
	Standard de	leviation		55.5				10.5			146.8			726.5	58.6 -	73.9				42.1 -	51.3	50.6	427.2			16.9	16.4	134.9	22.0		2.29	4.95	2.40	1.93	1.72	0.12	0.25	0.10	0.09		Modal PRE cat
				6.5				7.4			49.1			22.9	4.3 -	0.2				3.0 -	0.1	0.1	146.8			0.1	0.1	36.0	22.3		1.39	3.22	1.00	0.92	1.45	0.08	0.19	0.06	0.05	0.09	Modal TP
				3.4	3.4			4.3	0.13	2.13E+10	25.9			20.5	3.1 1.38E+11	0.1				1.9 2.43E4		0.1	84.3		4.74E+09	0.0	0.0	15.6	13.3		0.75	1.62	0.55	0.45	0.85	0.05	0.10	0.04	0.03	0.05	Bags
				3.5	3.5	31		4.3			26.8			26.8	2.9 -	0.1				1.8 -	0.1	0.1	81.7	0.4		0.0	0.1	15.2	13.1		0.81	1.85	0.58	0.54	0.83	0.05	0.11	0.04	0.03	0.05	Modal Dil
	Type A unc	certainty		32.0	31.5	19.	3.8 2	23.4			84.8	8	4.2	419.4	33.8 -	42.6	41.7	454	1.8	24.3 -	29.6	29.2	246.6	40.0		9.7	9.5	77.9	12.7	-	1.32	2.86	1.38	1.12	0.99	0.07	0.14	0.06	0.05	0.06	Modal PRE cat
				3.8		28		4.3			28.4		7.3	13.2	2.5 -	0.1		38		1.8 -	0.1	0.1	84.8	0.4		0.1	0.1	20.8	12.9		0.80	1.86		0.53	0.83	0.05		0.04	0.03		Modal TP
Mear	n TWC effectiv	veness (pre-b	ag)	92.7		% 5	3.9%	99.4%	-		76.0	%	76.9%	84.0%	97.0% -	99.95			7.3%	99.7% -	99.9%	99.95	6 96.5%	99.8%	-	99.9%	99.9%				1	•									
Max	TWC effective	reness (pre-ba	g)	93.2	% 93.5	% 9	4.3%	99.6%		-	77.5	%	78.5%	84.8%	97.4% -	100.05	6 100.	0% 9	7.8%	99.9% -	100.0%	100.05	6 98.1%	99.8%	-	99.9%	99.9%	99.4%	99.9	% -]										
	THE ALL AND	eness (pre-ba	(g)	92.1	% 92.3	6 9	3.2%	98.9%	-	-	74.4	«<	75.3%	83.2%	96.6% -	99.95	6 99.	9% 9	6.6%	99.5% -	99.9%	99.99	6 93.5%	99.7%		99.9%	99.8%	98.1%	98.4	% -	1										
Min	Twc enecuve	circos (pic bi																																							
Mear	TWC effective	veness (pre-p	ost)	91.5				99.3%		-	72.0		73.2%	84.1%	96.7% -	99.95	6 99.	9% 9	7.2%	99.7% -	100.0%	99.99	6 96.2%	99.8%		99.9%	99.9%	98.5%	99.4	% -											
Mear		veness (pre-p	ost)		% 91.9	% 9	3.8%			-		%								99.7% -	100.0%					99.9% 100.0%															



Table 9Emissions and fuel consumption results from the Fiat Tipo 1.4 vehicle over the WLTCcycle for TWC Low S at 50 cycles

	utomotive F	Research and Deve imissions Testing Li	elopment	t Institute Ltd																	W	LTP te	est (R	eg 201	17/115	i1) - WI	LTC dr	iving o	cycle															
VIN: ZFA3560	0006K20	252			Vel	hicle r	nodel:						Fiat ⁻	Гіро 1.4	LPG								Emis	ssion sta	andard:	Euro 6								Ту	yres:			Conti	inental Cont	EcoContact	5 225/45 R17	V XL		
Inertia [kg]:		1509					Emission	n WLTC					E	mission LO	W			E	mission M	IDDLE				Emi	ission HIG	H			En	nission Ex-H	IGH				CO ₂ emissi	on				Fuel co	nsumption			
		Chassis dyno	1				[mg/	'km]						[mg/km]					[mg/kn	1]					[mg/km]					[mg/km]					[g/km]					[l/10	0 km] ⁽²⁾			Note 1
Mileage[km]	Date	F0/F1/F2	Test N	No. THC	NMHC	5	co	NOx	PM	PN		THC	NMHC	co	NO	PN	THC	NMHC	CO	NO	C PI	N T	THC	NMHC	CO	NOx	PN	THC	NMHC	со	NOx	PN	WLTC	LOW	MIDDLE	HIGH	Ex-HIGH	WLTC	C LC	W M	DDLE	HIGH E	Ex-HIGH	
Ageing stage:	50 cvcles			BAG - MO	DDAL DIL -	PRE - P	OST		-						1	1		1	1	1				-	1		1		1	1	1	1			1	1	1			1				
		45.1	1	51	47		545	32	0.57	7 4.80E+	11	379	348	3242	89	3.26E+12	1	1	350	3	4.51E	+10	0	0	128	19	2.28E+10	1	1	9	39	8.60E+10	150.6	222.4	148.3	129.2	143.5	9.32	14	.06 9	9.15	7.96	8.83	Bags
4 603	2018-12-0	-0.87	L1-05	54	49		545	32	-	-		395	362	3230	90	-	2	1	351	3	- 1		1	1	130	19	-	1	1	9	39	-	151.5	223.0	148.6	129.6	145.4	9.38	14	.10 9	0.17	7.99	8.94	Modal Dil
4 003	2010-12-0	0.0390	L1-05	609	579		7907	2349	-	-		1399	1323	17089	132		644	613	10848	159	9 -	4	474	453	6104	2107	-	410	391	4336	3378	-	138.6	205.2	132.8	115.9	136.6	9.40	14	.53 9	9.34	7.81	8.90	Modal PRE cat
				70	65		608	43		-		526	485	3700	108		1	1	343	2	-		0	0	129	17	-	1	1	17	63	-	154.6	227.7	151.5	132.2	148.4	9.58	14	.46 9	9.35	8.14	9.13	Modal TP
		TWC effectivenes					93.1%			-		72.9%	73.7%			.2% -	99.9%				.8% -		99.9%	99.9%	97.9%			99.8%																TWC eff
	т	WC effectivenes	s (pre-p			.8%	92.3%	98.2%		-		62.4%	63.3%			.8% -	99.9%	99.95		8% 99	.9% -		99.9%	99.9%	97.9%			99.9%								,								TWC eff
		45.1		57	53		520	21	0.52			429	395	3320	91		1	1	178	7	4.18E		0	0	105	9	1.79E+10	0	0	30	13	7.38E+10	150.2	221.2	146.7	128.9		9.30					8.86	Bags
4 627	2018-12-0	-0.87	L1-05	58	53		520	20	· ·			433	397	3314	90		2	1	180				1	0	107	9	· .	1	1	30	13	· ·	151.0	221.8	147.0	129.1		9.35					8.97	Modal Dil
		0.0390		597	568		7066	2686		-		1533	1464	14519	161	5 -	596	568	8309		5 -			418	5910	2450	-	383	363	4564	3612	-	144.0	202.7	138.5	123.9	-	9.65	_				9.28	Modal PRE cat
				62			507	22	-	-	_	465	426	3133	98	-	1	1	194	7	-		0	0	120	9	-	0	1	39	12	-	155.5	220.1	153.4	134.4	150.8	9.62	13	.92 9	9.45	8.28	9.28	Modal TP TWC eff
		TWC effectivenes				.7%	92.6%	99.2%				72.0%	73.1%			.4% -	99.8%				.7% - .7% -			100.0%	98.2%			99.9% 99.9%															-	TWC eff
r	1	45.1	s (pre-p	057) 89.6 60			583	21	0.59	e.30E+	11	448	409	3669	76 93		99.8%	99.8	195				1	99.9%	98.0%		1.56E+10	99.9%	99.8%	20		4.28E+10	149.6	219.6	146.5	128.6	143.2	9.26	12	.95	9.03	7.93	0.01	Bags
		.0.87		63	58		583	20	0.56			465	425	3661	77		3	2	196	10			2	1	158	7	-	1	1	20	17	4.200-110	150.4	220.4	146.9	128.9		9.32					8.91	Modal Dil
4 650	2018-12-0	0.0390	L1-05	63 589			7101	2670	1 .			1509	1433		167		578	551	8127					436	5887	2468	<u> </u>	366	347	4445	3526	-	144.4	206.1	-	124.2	-	9.68	_				9.22	Modal PRE cat
		0.0000		67	61		579	22	+ .	-		501	456	3535	86		1	1	217				0	0	174	7		1	1	28	18	· .	155.8		153.7	134.7		9.65					9.22	Modal TP
	1	TWC effectivenes	ss (pre-b		_		91.8%		% -			70.3%	71.4%				99.7%	99.85	1		.5% -			99.9%	97.3%			99.7%				6 -				1	1							TWC eff
		WC effectivenes				.1%	91.9%	99.2%		-		66.8%	68.2%			.9% -	99.8%				.5% -		99.9%	99.9%	97.0%			99.8%															ľ	TWC eff
				56	52	· ·	550	25	0.56	5.61E+	11	419	384	3410	87		1	1	241	6			0	0	130	12	1.88E+10	1	1	19	23	6.75E+10	150.1	221.1	147.2	128.9	143.6	9.29	14	.00 9	9.08	7.94	8.83	Bags
				59	53		549	24		-		431	395	3402	86		2	1	242	6	-		1	1	132	12	-	1	1	20	23		151.0	221.8	147.5	129.2	145.4	9.35	14	.05 9	9.10	7.96	8.94	Modal Dil
	Mea	in values		598	569		7358	2569		-		1480	1407	15673	153	7 -	606	577	9095	195	7 -	4	457	436	5967	2341	-	386	367	4448	3505	-	142.3	204.7	136.8	121.3	140.4	9.57	14	.38 9	9.40	8.12	9.13	Modal PRE cat
				67	61		564	29	-	-		497	455	3456	97	-	1	1	251	7	-		0	0	141	11	-	1	1	28	31	-	155.3	223.9	152.9	133.8	149.7	9.62	14	.19 9	0.43	8.24	9.21	Modal TP
				3.9	3.6		26.0	5.4	0.03	6.14E+	10	29.0	26.3	185.5	4.4	5.18E+11	0.3	0.2	77.3	3.0	2.96E	+09 0	0.2	0.2	21.1	5.3	2.98E+09	0.3	0.2	8.5	11.6	1.82E+10	0.42	1.13	0.79	0.25	0.35	0.02	0	05 (0.06	0.01	0.02	Bags
	Standar	rd deviation		4.0			25.7	5.5	-	-		28.7	26.1	186.4	6.0		0.4	0.3	77.2					0.2	20.9	5.3	-	0.3	0.3	8.6	11.5	-	0.45	1.09	0.79	0.30		0.03					0.03	Modal Dil
	Standar	u uctilution		8.2			388.3	155.1	· ·	-		58.5	60.8		155.		27.8	26.1	1242.0					14.4	97.7	166.0	-	18.1	18.3	93.0	96.2		2.64	1.44	2.84	3.81		0.12					0.17	Modal PRE cat
				3.4			42.6	9.7	-			25.3	24.4		9.2		0.2	0.1	65.4					0.0	23.7	4.3	-	0.1	0.1	8.9	22.8		0.52	3.13	0.97	1.13		0.03					0.06	Modal TP
				2.3			15.0	3.1	0.02			16.7		107.1	2.5		0.2	0.1	44.7					0.1	12.2		1.72E+09	0.1	0.1	4.9	6.7	1.05E+10	0.24	0.65	0.46	0.14		0.01					0.01	Bags
	Type A u	uncertainty		2.3			14.8	3.2	· · ·			16.6	15.0		3.5		0.2	0.2	44.6					0.1	12.1	3.1		0.2	0.2	5.0	6.6	· ·	0.26	0.63	0.46	0.17		0.01					0.01	Modal Dil
				4.7			224.2	89.6				33.8	35.1		89.7		16.1	15.1	717.0					8.3	56.4	95.9	· · ·	10.5	10.6	53.7	55.6		1.52	0.83	1.64	2.20		0.07					0.10	Modal PRE cat
Maria				2.0		_	24.6	5.6				14.6	14.1		5.3		0.1	0.1	37.8					0.0	13.7	2.5	· ·	0.1	0.0	5.2	13.2	-	0.30	1.81	0.56	0.65	0.59	0.02	0.	13 (0.03	0.04	0.04	Modal TP
		ctiveness (pre-b		90.6		.9%	92.5%					71.7%	72.7%				99.8%						99.9% L00.0%	99.9% 100.0%	97.8%			99.8%																
		ctiveness (pre-b ctiveness (pre-b		91.6		.9%	93.1%					72.9%	73.7%			.2% -	99.9%				.8% -				98.2%			99.9%																
		ctiveness (pre-p ctiveness (pre-p		89.7		.2%	91.8% 92.3%				_	70.3%	71.4%			.2% -	99.7% 99.8%				.5% - .7% -		99.9% 99.9%	99.9% 99.9%	97.3% 97.6%			99.7% 99.8%																
		ctiveness (pre-p		88.5		.3%	92.3%	98.9%				69.7%	70.9%			.9% -	99.8%				.9% -		99.9% L00.0%	99.9%	97.6%			99.8%																
		tiveness (pre-p		89.6		.0%	92.8%					69.7%	63.3%			.9% -	99.9%				.9% -			99.9%	98.0%			99.9%																
win, I	VVL ETTEC	.uveness (pré-po	ustj	88.4	• 70 88.	.0%	31.3%	98.2%	70] -	-		6Z.4%	65.3%	11.19	70j 91	.070 -	99.8%	1 33.82	70g 96.	070 99	.3% -		53.5%	33.3%	97.0%	99.2%	-	99.8%	99.8%	ay 99.1%	98.1	- io												



Table 10 Emissions and fuel consumption results from the Fiat Tipo 1.4 vehicle over the WLTC cycle for TWC Low S at 100 cycles

	Automotive Re	search and Deve issions Testing L	elopment	nstitute Ltd																WLT	P test (F	Reg 20	17/115	1) - WI	LTC dri	iving c	ycle														
'IN: ZFA35F	600006K2025	52			Veh	icle mo	del:					Fia	t Tipo	1.4 LPG							En	nission s	tandard:	Euro 6								Tyr	es:			Contine	ntal ContiEcol	ontact 5 225/4	R17 V XL		
nertia [kg]:		1509				Er	nission V	NLTC					Emissio	n LOW			E	nission MIE	DLE			E	mission HIG	H			En	hission Ex-HI	GH			C	CO ₂ emissio	n			F	uel consump	tion		
/ileage(km)	Date	Chassis dyno	Test N				[mg/km])]					[mg/	km]			,	[mg/km]					[mg/km]					[mg/km]					[g/km]	,				[l/100 km] (2			Note 1
leage[kiii]	Date	F0/F1/F2	Testine	THC	NMHC	0	>	NOx	PM	PN	THC	NMHC	: c	0	NOx PN	THC	NMHC	co	NOx	PN	THC	NMHC	co	NOx	PN	THC	NMHC	co	NOx	PN	WLTC	LOW	MIDDLE	HIGH	Ex-HIGH	WLTC	LOW	MIDDLE	HIGH	Ex-HIGH	
geing stage	: 100 cycles			BAG - MO	DAL DIL - F	RE - POS	т																											-							
		45.1	1	66	61	68			0.58	6.26E+11	487	451			108 4.44E+12	1	1	209		5.84E+10	1	1	440	5	1.66E+10	1	1	68		4.87E+10	152.4	223.0	148.8	130.2	147.1	9.45	14.16		8.05	9.05	Bags
4 697	2019-01-03	-0.87	L1-000	70	64	67		18			511	474			107 -	3	2	210	6		2	1	441	5		1	1	69	3		153.2	223.6	149.2	130.5	148.7	9.50	14.19	9.20	8.07	9.15	Modal Dil
		0.0390		669	640	82		2351	1.1		1541 650	1467			1409 - 123 -	743	714	10027	1668		539	517	7404	2022		411	392	4804	3387		140.3 156.3	207.3	131.9 152.1	117.0	140.3	9.55	14.63		8.01	9.17 9.34	Modal PRE cat Modal TP
							2 1.7%	20 99.2%			650				123 - 92.3% -	2 99.8%			5		1 99.8%	1 99.8%				1 99.8%					156.3	228.4	152.1	133.1	151.7	9.70	14.57	9.38	8.23	9.34	Modal TP TWC eff
		VC effectivenes					0.6%	99.2%			57.9				92.3% -	99.8%					99.8%	99.8%		99.8%		99.8%														1	TWC eff
	///	45.1	s (pre-po	70	64			21	0.63	6.47E+11	514	469			97 4.44E+12	2	1	372		4.91E+10	1	1	157	5	1.62E+10	1	1	66	4	1.00E+11	150.8	219.2	148.8	129.8	144.2	9.36	14.01	9.19	8.00	8.87	Bags
		-0.87		73	67	74		20			536	490			92 -	3	2	373	23		1	1	159	5	-	1	1	68	4		151.5	219.5	149.0	130.2	145.6	9.40	14.02		8.03	8.96	Modal Dil
4 721	2019-01-03	0.0390	L1-000	2 663	631	87	7	2336		-	1558	1466	19	540	1224 -	716	684	10879	1657		519	497	6908	2134	-	418	399	4897	3326	-	138.4	200.8	132.1	117.9	136.2	9.48	14.52	9.31	8.02	8.93	Modal PRE cat
				96	88	82	7	22		-	711	654	50	60	105 -	1	1	340	26	-	0	1	165	6	-	1	1	76	4	-	154.6	224.3	151.9	132.8	148.6	9.61	14.41	9.38	8.19	9.14	Modal TP
	n	WC effectivene:	ss (pre-ba	g) 89.5	6 89.9	1% 9	1.4%	99.1%			67.0	% 68.	0%	77.2%	92.1%	99.8%	99.89	96.6	6 98.59		99.9%	99.9%	97.7%	99.8%		99.8%	99.8%	98.6%	99.9%	6 -						1				-	TWC eff
	ТИ	/C effectivenes	s (pre-po	st) 85.5	6 86.0	1% 9	0.5%	99.0%	1.0		54.3	% 55.	4%	74.1%	91.4% -	99.8%	99.89	96.9	6 98.49		99.9%	99.9%	97.6%	99.7%		99.9%	99.8%	98.5%	99.9%	6 -											TWC eff
		45.1		57	53				0.78	5.31E+11	424	390			114 3.82E+12	1		91		4.66E+10	1	1	86		8.07E+09	1	1	118		3.38E+10	148.6	214.1	144.7	127.5		9.20	13.58		7.85		Bags
4 744	2019-01-04	-0.87	L1-000	4 61	55	54		20			444	408			110 -		2	92	14	-	2	1	87	5		2	1	119	3		149.4	214.6	145.0	127.9	146.3	9.25	13.62	8.93	7.87	9.01	Modal Dil
		0.0390		658	629			2343	-	-	1521	1445			1317 -	730		8900	1657		533	513	6111	2125	-	401	382	4926	3313	-	137.4	197.8	129.1	116.3		9.32	14.07		7.84	9.03	Modal PRE cat
				76	71			22			570	526			128 -	1	1	95	14		0	0	84	4		1	1	123	2		152.4	219.1	147.8	130.4	149.2	9.45	13.95	9.10	8.03	9.19	Modal TP
		WC effectivenes					2.8%	99.1%			72.1				91.4% -	99.8%					99.9%	99.9%		99.8%		99.8%															TWC eff
	TW	/C effectivenes	s (pre-po	/		65	2.2%	99.1% 20	-	6.02E+11	62.5				90.3% · · · · · · · · · · · · · · · · · · ·	99.8%				5.14E+10	99.9%	99.9%	98.6% 228	99.8%	1.36E+10	99.8%	99.8%			6.10E+10	150.6	218.8	147.4	100.0	145.3	9.34	13.91	9.09	7.97	0.01	TWC eff
				64	59 62	65		19	0.00	0.02E+11	475	437			106 4.23E+12 103 -	2	2	224	15	0.14E+10	1	1	228	5	1.30E+10	1	1	84	4	6.10E+10	151.4	218.8	147.4	129.2	140.3	9.34	13.91		7.97	9.04	Bags Modal Dil
	Mean	values		663	633	82		2343			1540	1459			1316 -	730	700	9935	1661		530	509	6808	2094		410	391	4876	3342		131.4	202.0	131.0	117.1	138.1	9.45	14.41	9.15	7.96	9.04	Modal PRE cat
				87	80	73		21			644	594			119 -	1	1 1	225	15		0	1	235	5		1	1	92	3		154.4	223.9	150.6	132.1	149.8	9.59	14.31	9.29	8.15	9.22	Modal TP
				5.3	4.7			1.3	0.09	5.04E+10	37.6	33.7			7.1 2.94E+11	0.1	0.2	115.1		5.08E+09	0.1	0.1	152.6	0.2	3.94E+09	0.1	0.1	23.7	0.7	2.86E+10	1.54	3.68	1.94	1.19	1.26	0.10	0.24	0.13	0.09	0.08	Bags
				5.3	4.9	81	8	0.9			38.9	35.5	43	7.5	7.9 -	0.1	0.1	115.1	6.9		0.2	0.1	153.0	0.2	-	0.1	0.0	23.8	0.6		1.54	3.69	1.94	1.20	1.33	0.10	0.24	0.13	0.08	0.08	Modal Dil
	Standard	deviation		4.7	4.7	420		6.0	-		14.9	10.4	13		75.5 -	11.3	12.4	810.7	4.9		8.3	8.6	532.6	51.0		7.0	7.0	52.2	32.3		1.21	3.94	1.38	0.68	1.67	0.10	0.24	0.16	0.08	0.10	Modal PRE cat
				8.0	7.3	96	2	1.3			57.7	52.3	51	5.3	9.7 -	0.1		100.7	8.5		0.1	0.1	160.4	0.5		0.1	0.1	21.7	0.7		1.58	3.78	1.99	1.22	1.35	0.11	0.26	0.13	0.09	0.08	Modal TP
				3.0	2.7			0.7	0.05	2.91E+10	21.7	19.5			4.1 1.70E+11	0.1	0.1	66.5		2.93E+09	0.1	0.1	88.1		2.27E+09	0.0	0.0	13.7	0.4	1.65E+10	0.89	2.13	1.12	0.69	0.73	0.06	0.14	0.07	0.05	0.04	Bags
	Type A ur	certainty		3.1	2.9			0.5		-	22.5	20.5			4.6 -	0.1	0.1	66.5	4.0		0.1	0.0	88.3	0.1		0.1	0.0	13.7	0.4	-	0.89	2.13	1.12	0.69	0.77	0.06	0.14	0.07	0.05	0.05	Modal Dil
	.,pe A u	recruitity		2.7	2.7			3.5			8.6	6.0			43.6 -		7.2	468.0	2.8		4.8	5.0	307.5	29.4		4.1	4.0	30.1	18.6		0.70	2.27	0.80	0.39	0.96	0.06	0.14		0.05	0.06	Modal PRE cat
				4.6	4.2			0.7			33.3	30.2			5.6 -	0.0		58.1	4.9		0.0	0.0	92.6	0.3		0.1	0.0	12.5	0.4		0.91	2.18	1.15	0.70	0.78	0.06	0.15	0.08	0.05	0.05	Modal TP
		tiveness (pre-b		90.3			2.0%	99.1%	1.1		69.2				91.9% ·	99.8%					99.9%	99.9%		99.8%		99.8%															
		iveness (pre-b		91.3			2.8%	99.2%	-	-	72.1				92.3% -	99.8%					99.9%	99.9%		99.8%		99.8%	99.8%														
		iveness (pre-b		89.5				99.1%	1.1		67.0				91.4% -	99.8%					99.8%	99.8%				99.8%															
		iveness (pre-p		86.9			1.1%	99.1%			58.2				91.0% -	99.8%					99.9%	99.9%	96.7%	99.8%		99.8%	99.8%														
Max	I WUL effecti	veness (pre-p		88.4			2.2%	99.2% 99.0%				% 63. % 55.			91.4% -	99.8%					99.9% 99.9%	99.9% 99.9%		99.8% 99.7%		99.9% 99.8%															



Table 11 Emissions and fuel consumption results from the Fiat Tipo 1.4 vehicle over the WLTC cycle for TWC Low S at 175 cycles

	Automotive Re	SAAA search and Deve ssions Testing La	elopment l	institute Ltd														WLTP	test (F	Reg 201	7/115 ⁻	1) - WL	TC dr	iving c	cycle														
VIN: ZFA356	00006K2025	2			Vehi	cle mode	1:				Fiat T	Гіро 1.4 L	PG						En	nission sta	ndard: I	Euro 6								Tyr	es:			Continer	tal ContiEcoC	ontact 5 225/45	5 R17 V XL		
Inertia [kg]:		1509					sion WLTC				Er	mission LOV	/		En	mission MID	DLE				sion HIG	н			Er	nission Ex-H	GH			C	O2 emissio	n			Fi	iel consump	otion		
Mileage[km]	Date	Chassis dyno	Test No				mg/km]	1	1		1	[mg/km]			1	[mg/km]	1				[mg/km]					[mg/km]		1			[g/km]	1	1		1	[I/100 km] ⁽²⁾	1	T	Note 1
		F0/F1/F2		THC	NMHC	co	NOx	PM	PN	THC	NMHC	со	NOx PN	THC	NMHC	co	NOx	PN	THC	NMHC	co	NOx	PN	THC	NMHC	co	NOx	PN	WLTC	LOW	MIDDLE	HIGH	Ex-HIGH	WLTC	LOW	MIDDLE	HIGH	Ex-HIGH	
Ageing stage:	175 cycles		1		DAL DIL - PI																																		-
		45.1	1	64	63	527	23	0.64	5.04E+11	472	439	3365 3360	116 3.57E+12 116 -	3	1	141	11 3	.09E+10	1	0	105	11 10	1.16E+10	1	1	46	5	4.99E+10	147.8 148.6	212.7	143.4 143.6	127.9	143.2	9.15	13.50 13.57	8.84	7.88	8.81	Bags Modal Dil
4 814	2019-01-22	-0.87 0.0390	L1-0019	9 666	63	7831	23			497	462	3360	116 -	3 738	2 710	9427	11 1614		513	1 493	6396	2108		2 401	383	47 4574	5 3353		148.6	213.8 196.4	143.6 126.3	128.3	144.6	9.20	13.57	8.84	7.90	8.90	Modal Dil Modal PRE cat
		0.0390		87	81	593	2347	1		644	600	3795	135 -	2	1	140	8		1	493	123	14		1	1	45/4	4		151.6	218.4	146.3	130.9	147.6	9.40	13.92	9.01	8.06	9.08	Modal TP
	TV	/C effectivenes	ss (pre-ba					*		70.7%				99.8%					99,9%	99.9%	98.4%			99.7%				6	101.0	210.4	140.0	100.0	147.0	3.40	10.94	3.07	0.00	3.00	TWC eff
		C effectiveness								60.0%				99.8%					99.8%	99.8%	98.1%			99.7%			99.99												TWC eff
		45.1		67	62	610	22	0.75	6.56E+11	498	459	3938	120 4.64E+12	2	1	166	13 €	.43E+10	1	0	53	7	1.45E+10	1	1	102	4	5.87E+10	147.9	214.5	143.6	126.6	143.9	9.17	13.67	8.85	7.79	8.86	Bags
4 837	2019-01-23	-0.87	L1-0022	71	65	608	22		-	520	480	3916	120 -	3	2	169	13	-	1	1	54	7	-	1	1	101	4	-	148.6	215.1	144.0	127.1	145.1	9.21	13.70	8.87	7.82	8.93	Modal Dil
4007	2010-01-20	0.0390	21-0023	609	581	7231	2601			1431	1365	14399	1555 -	667	639	8431	2040		485		5991	2404		374	355	4928	3488	-	140.4	193.4	132.3	121.1	142.1	9.45	13.55	9.08	8.11	9.29	Modal PRE cat
				73	68	589	24		1.1	546	503	3703	131 -	2		178	14		1	1	65	8		1	1	113	4		152.1	209.2	148.0	132.0	150.6	9.43	13.33	9.12	8.12	9.27	Modal TP
		/C effectivenes								65.2%				99.7%				-	99.9%	99.9%	99.1%		-	99.7%															TWC eff
	TW	C effectiveness	s (pre-pos	st) 87.9	61	6 91.9 807	% 99.1% 23		5.97E+11	61.9% 495	63.2% 456	74.3%	91.6% - 121 4.23E+12	99.7%		6 97.9% 152		- 69E+10	99.9%	99.9%	98.9% 334		1.43E+10	99.7%	99.7%	97.7%	99.99	6.34E+10	146.5	212.5	142.1	125.4	142.6	9.10	13.62	8.76		8.78	TWC eff Bags
		45.1 -0.87		74	65	807	23	0.83	5.9/E+11	495 519	400	4808	121 4.23E+12 122 -	3	2	152	13 3	09E+10	1	1	335	7	1.43E+10	2	1	90	6	0.34E+10	140.5	212.5	142.1	125.9	142.0	9.10	13.62	8.76	7.74	8.78	Modal Dil
4 837	2019-01-24	-0.87	L1-0027	7 631	603	7720	2556			1517	1447	15587	1498 -	697	668	8801	2009		500		7010	2240		375	357	4761	3545		139.1	195.5	130.6	117.4	144.1	9.42	13.80	9.01	7.99	9.25	Modal PRE cat
		0.0350		73	67	789	25			541	496	4582	131 -	2	1	164	14		1	1	352	7		1	1	110	7		151.4	212.3	147.0	129.4	150.3	9.40	13.60	9.06	7.99	9.25	Modal TP
	TV	/C effectivenes	ss (pre-ba					× ·		67.3%				99.7%	99.8%				99,9%	99.9%	95.2%	99.7%		99.7%	99.7%		99.89	6 -									1		TWC eff
		C effectiveness								64.3%				99.7%					99.9%	99.9%	95.0%	99.7%		99.7%			99.89												TWC eff
				66	61	648	23	0.74	5.85E+11	489	451	4037	119 4.15E+12	2	1	153	12 4	.41E+10	1	1	164	8	1.35E+10	1	1	81	5	5.74E+10	147.4	213.2	143.1	126.6	143.2	9.14	13.60	8.81	7.80	8.82	Bags
	Mean			70	64	646	23		-	512	473	4019	119 -	3	2	154	12	-	1	1	165	8	-	2	1	82	5	-	148.2	214.0	143.3	127.1	144.6	9.19	13.64	8.83	7.83	8.90	Modal Dil
	weatt	values		635	607	7594	2499			1519	1449	15776	1454 -	701	672	8886	1888		500		6466	2251	-	384	365	4754	3462		138.7	195.1	129.7	118.5	140.2	9.38	13.80	8.97	8.00	9.16	Modal PRE cat
				78	72	657	25	-		577	533	4027	132 -	2	1	161	12	-	1	1	180	10	-	1	1	93	5	-	151.7	213.3	147.1	130.7	149.5	9.41	13.61	9.06	8.06	9.20	Modal TP
				1.5	1.1	117.4		0.08	6.26E+10	11.7	8.8	593.0	2.0 4.43E+11	0.4	0.2	10.6	1.1 1		0.0	0.1	121.8		1.34E+09	0.1	0.1	25.0	0.8	5.60E+09	0.65	0.92	0.66	1.03	0.53	0.03	0.07	0.04	0.06	0.03	Bags
	Standard	deviation		1.3	1.0	116.2			· ·	10.9	8.1	584.5	2.5 -	0.2	0.1	11.0	1.2	-	0.0		121.9	1.6	-	0.1	0.1	24.6	0.8		0.62	0.83	0.68	0.98	0.42	0.03	0.06		0.05	0.03	Modal Dil
				23.6	23.2	260.9	113.6			72.8	68.9	1209.7	105.8 -	29.2	29.5	410.9	193.8	-	11.7		419.0	121.0		12.7	12.8	144.7	80.5		1.65	1.27	2.55	1.84	2.47	0.08	0.21	0.11	0.09	0.16	Modal PRE cat
				6.5	6.5	93.7 67.8	0.6	0.05	3.62E+10	47.3 6.8	47.4	394.6 342.4	2.1 1.2 2.56E+11	0.2	0.1	15.6	2.6		0.1	0.1	123.7	3.2	- 7.72E+08	0.1	0.1	26.2	1.1	3.23E+09	0.30	3.82	0.67	1.03	1.35	0.01	0.24	0.04	0.05	0.09	Modal TP Bags
				0.9	0.6	67.1	0.2	0.05	3.62E+10	6.3	4.7	342.4	1.2 2.00E+11 1.4 -	0.2	0.1	6.3	0.7 8	-	0.0	0.0	70.3	0.9	7.72E+08	0.1	0.1	14.4	0.5	3.23E+09	0.36	0.53	0.38	0.60	0.31	0.02	0.04	0.02	0.03	0.02	Modal Dil
	Type A un	certainty		13.6	13.4	150.6		1 .		42.0	39.8	698.4	61.1 -	16.9	17.0	237.3	111.9		6.7		241.9	69.9		7.3	7.4	83.5	46.5		0.96	0.48	1.47	1.06	1.43	0.02	0.03		0.05	0.09	Modal PRE cat
				3.7	3.7	54.1	0.3	1 .		27.3	27.4	227.8	1.2 -	0.1	0.0	9.0	1.5		0.1		71.4	1.8		0.1	0.0	15.1	0.7	1 .	0.17	2.20	0.39	0.60	0.78	0.04	0.14	0.00	0.03	0.05	Modal TP
Mean	TWC effect	veness (pre-b	oag)	89.6				× ·		67.7%				99.7%			99.3%		99,9%	99.9%	97.6%			99.7%	99.7%			6 -											
Max.	TWC effecti	veness (pre-b	ag)	90.4						70.7%				99.8%			6 99.3%	-	99.9%	99.9%	99.1%			99.7%	99.8%														
Min.	TWC effecti	eness (pre-ba	ag)	89.0			% 99.0%	% -		65.2%	66.4%	69.2%	91.1% -	99.7%	99.8%		99.3%	-	99.9%	99.9%	95.2%			99.7%	99.7%			6 -											
Mean	TWC effecti	veness (pre-p	oost)	87.8	6 88.2	6 91.4	% 99.0%	× -	1.1	62.1%	63.3%	74.3%	90.8% -	99.7%	99.8%	98.2%	99.4%		99.9%	99.9%	97.3%	99.6%	-	99.7%	99.7%	98.1%	99.99	6 -											
Max.		veness (pre-po reness (pre-po		88.4	6 88.9	6 92.4	% 99.1%	% -	1.1.1	64.3%			91.6% -	99.8%	99.8%	98.5%	6 99.5%	1.00	99.9%	99.9%	98.9%	99.7%	-	99.7%	99.7%	98.8%	99.99	6 -											



Table 12 Emissions and fuel consumption results from the Fiat Tipo 1.4 vehicle over the WLTC cycle for TWC Low S at 250 cycles

BOSMAL Auto	motive Res	SAAA search and Deve ssions Testing Li	lopment ir	nstitute Ltd															WLTF	P test (Reg 20	17/115	1) - WL	TC dri	ving c	ycle														
IN: ZFA356000	006K20252	2			Vehi	le mode	l:				Fiat 1	Tipo 1.4 L	PG							Er	nission st	andard:	Euro 6								Tyre	is:			Continen	ntal ContiEcoCo	intact 5 225/45	5 R17 V XL		
ertia [kg]:		1509				Emis	sion WLTC				Er	nission LOV	1			Emis	sion MIDE	DLE			Err	ission HIG	н			Emi	ssion Ex-HIG	н			С	O₂ emissio	n			Fr	uel consump	ation		
		Chassis dyno	_				mg/km]					[mg/km]					[mg/km]					[mg/km]					[mg/km]					[g/km]					[l/100 km] (2)	1		Note 1
leage[km]	Date	F0/F1/F2	Test No.	THC	NMHC	co	NOx	PM	PN	THC	NMHC	co	NOx	PN	THC	NMHC	co	NOx	PN	THC	NMHC	co	NOx	PN	THC	NMHC	co	NOx	PN	WLTC	LOW	MDDLE	HIGH	Ex-HIGH	WLTC	LOW	MDDLE	HIGH	Ex-HIGH	
eing stage: 25	0 cycles			BAG - MOI		F - POST																														L	<u> </u>			
		45.1		55	50	618	23	0.75	5.05E+11	402	365	3861	131	3.57E+12	2	1	203	10	3.77E+10	1	1	175	6	2.24E+10	2	2	24	6	4.64E+10	149.4	218.1	146.0	128.0	144.3	9.26	13.86	9.00	7.89	8.88	Bags
		-0.87	I	60	52	618	23	1.		421	383	3855	128		4	2	205	10		2	1	177	6		3	2	25	6	-	150.3	218.7	146.7	128.5	145.7	9.32	13.90	9.04	7.92		Modal Dil
5 188 21	1.03.2019	0.0390	L1-0160	586	558	7499	2344		-	1337	1264	15859	1313	-	651	624	9409	1671		469	449	6204	2063		367	350	4387	3363	-	139.0	202.9	131.8	116.9	138.3	9.38	14.26	9.14	7.88	9.00	Modal PRE ca
				70	64	687	25		-	519	471	4348	152	-	2	1	218	7	-	1	1	178	5	-	2	2	27	4	-	153.3	223.3	149.6	131.1	148.6	9.51	14.25	9.22	8.08	9.14	Modal TP
	TW	C effectivenes	s (pre-bag	g) 90.6%	91.1	6 91.8	% 99.0	% -	1.11	69.9%	71.1%	75.7%	90.0%	6 -	99.7%	99.8%	97.8%	99.4%	1.1	99.8%	99.8%	97.2%	99.7%	1.1	99.4%	99.5%	99.5%	99.8%								-	-		-	TWC eff
	TWO	C effectiveness	s (pre-pos	t) 88.0%	88.6	6 90.8	% 98.9			61.2%	62.7%	72.6%	88.4%	5 -	99.7%	99.8%	97.7%	99.6%	-	99.9%	99.8%	97.1%	99.8%		99.4%	99.5%	99.4%	99.9%	-											TWC eff
		45.1		66		679	21	0.54	5.13E+11	479	438	4594		3.64E+12	3	2	199		2.50E+10	2	2	61	10	8.17E+09	3	2	24	9	6.08E+10	146.5		142.8	125.1	141.6	9.08	13.72			8.71	Bags
5 259 23	3.03.2019	-0.87	L1-0164	68	61	680	20			496	453	4593	93	-	3	1	201	9	-	1	1	63	9		2		24	8	-	147.3	215.3	143.0	125.7	142.9	9.13	13.77	8.82		8.79	Modal Dil
0100 10		0.0390	21-0104	604	575	7530				1483	1401	18221	1190		659	631	9143	1624		460	441	5643	2075		368	351	4229	3261	-	135.4		127.5	114.0		9.17	14.22			8.78	Modal PRE ca
				86	78	782	20			635	582	5345	106		2	1	201	7		1	1	65	7		2	1	28	7	-	150.2	220.0	145.8	128.2	145.7	9.33	14.17	8.99	7.89	8.96	Modal TP
		C effectivenes							-	67.7%					99.5%		97.8%	99.4%		99.6%		98.9%			99.3%		99.4%	99.7%												TWC eff
		C effectivenes	s (pre-pos I							57.2%					99.7%		97.8%	99.6%		99.8%		98.8%			99.5%			99.8%												TWC eff
		45.1 -0.87		58 61	53	720	25	0.48	5.54E+11	429	390	4662 4667	141	3.90E+12	2	2	260	6	5.58E+10	1	1	113 114	6	2.14E+10	2	1	43	10 9	5.68E+10	148.0	217.7	145.1	126.0	142.8	9.18 9.26	13.92 14.39	8.95 9.11	7.76	8.79	Bags Modal Dil
5 326 20	19-03-29	0.0390	L1-0178	594	565	7755	2283	- ·	<u> </u>	1417	1341	17166	1261		615	587	9788	1625	-	463	443	6128	2034		387	370	4486	3262		151.7	202.7	148.4	128.8	146.9	9.43	14.39	9.15	7.93	9.04	Modal PRE ca
		0.0390		76	69	835	2203			564	513	5540	150		2	1	273	5		403	1	98	4		1	1	4400	10		148.8		145.7	126.3	140.9	9.43	13.98	8.98			Modal TP
	TW	C effectivenes	r (pro-bay					× .		69.7%					99.6%		97.3%			99.8%		98.2%				99.6%		99.7%		140.0	210.7	140.7	120.0	144.7	3.20	1 10.00	1 0.50	1.10	0.07	TWC eff
		C effectivenes								60.2%					99.7%		97.2%			99.9%		98.4%			99.6%			99.7%												TWC eff
			- (J /	60	54	672	23	0.59	5.24E+11	437	398	4372	123	3.70E+12	3	2	220		3.95E+10	1	1	116		1.73E+10	2	2	30	8	5.46E+10	148.0	216.7	144.7	126.4	142.9	9.18	13.83	8.92	7.78	8.79	Bags
				62	56	673	22			455	414	4372	116		3	2	223	8		2	1	118	7		2	2	31	8	-	144.7	212.2	140.2	122.8	141.2	9.24	14.02	8.99	7.79	8.85	Modal Dil
	Mean v	alues		594	566	7594	2305			1412	1335	17082	1255		642	614	9447	1640	-	464	444	5991	2057		374	357	4367	3295		142.0	208.2	135.9	119.9	140.1	9.32	14.29	9.05	7.82	8.94	Modal PRE ca
				77	70	768	23			573	522	5078	136		2	1	230	6		1	1	113	5		2	2	33	7	-	150.8	220.7	147.0	128.5	146.1	9.36	14.13	9.06	7.92	8.99	Modal TP
				4.6	4.4	42.0	1.7	0.11	2.11E+10	32.0	30.3	362.6	18.3	1.42E+11	0.5	0.4	27.8	1.6	1.26E+10	0.5	0.4	46.8	1.8	6.47E+09	0.4	0.4	8.8	1.6	6.07E+09	1.22	1.66	1.36	1.22	1.09	0.07	0.08	0.08	0.08	0.07	Bags
	itandard d	deviation		4.1	3.8	42.4	1.3			30.9	29.1	366.3	16.2		0.1	0.2	27.4	1.5		0.1	0.2	46.8	1.7		0.3	0.2	8.9	1.4	-	5.86	6.90	6.79	6.21	4.55	0.08	0.26	0.12	0.10	0.08	Modal Dil
3	ocanciard c	Jeviation		7.6	7.2	114.2	28.0			59.5	56.2	965.9	50.2		19.1	19.2	264.5	21.9		3.8	3.5	248.5	17.3	-	9.3	9.3	105.9	47.8	-	7.02	10.97	9.02	6.40	5.04	0.11	0.07	0.14	0.13	0.11	Modal PRE ca
				6.4	6.0	61.0	2.5	-		48.0	45.6	521.9	21.2	-	0.1	0.1	30.6	1.1		0.1	0.1	47.3	1.1		0.3	0.2	7.8	2.2	-	1.90	1.95	1.81	1.95	1.88	0.12	0.11	0.11	0.12	0.11	Modal TP
				2.7	2.5	24.3	1.0	0.07	1.22E+10	18.5	17.5			8.18E+10	0.3	0.2	16.0	0.9	7.28E+09	0.3	0.2	27.0		3.74E+09	0.2	0.2	5.1	0.9	3.51E+09	0.70	0.96	0.79	0.70	0.63	0.04	0.05	0.05	0.05	0.04	Bags
1	ype A un	certainty		2.3	2.2	24.5	0.8	-		17.8	16.8	211.5	9.3		0.1	0.1	15.8	0.9		0.1	0.1	27.0	1.0	-	0.2	0.1	5.1	0.8	-	3.38	3.99	3.92	3.58	2.63	0.04	0.15	0.07	0.06	0.05	Modal Dil
	, a uni			4.4	4.2	65.9	16.1	-		34.3	32.4	557.7	29.0	-	11.0	11.1	152.7	12.6	-	2.2	2.0	143.5	10.0		5.4	5.4	61.2	27.6	-	4.06	6.33	5.21	3.70	2.91	0.07	0.04	0.08	0.07	0.07	Modal PRE ca
				3.7	3.5	35.2	1.4			27.7	26.3	301.3	12.2	-	0.1	0.1	17.7	0.7		0.1	0.0	27.3	0.6	-	0.1	0.1	4.5	1.3	-	1.10	1.13	1.04	1.13	1.08	0.07	0.06	0.06	0.07	0.07	Modal TP
		veness (pre-b		90.09					1.1	69.1%	70.3%				99.6%		97.7%			99.7%		98.1%	99.6%	1.1	99.4%		99.3%	99.8%												
		veness (pre-b		90.69					1	69.9%	71.1%		91.8%		99.7%		97.8%		-	99.8%		98.9%			99.6%		99.5%	99.8%	-											
Min. TW		reness (pre-b		89.19						67.7%					99.5%		97.3%			99.6%		97.2%			99.3%		99.1%	99.7%												
		veness (pre-p	ost)	87.09	87.6	6 89.9	% 99.0	% -		59.5%	61.0%	70.3%	89.2%	-	99.7%	99.8%	97.6%	99.6%	-	99.9%	99.8%	98.1%	99.7%		99.5%	99.6%	99.2%	99.8%	-											
			43																																					
Max. TW	/C effectiv	eness (pre-p		88.09					1.1	61.2% 57.2%					99.7% 99.7%		97.8% 97.2%			99.9% 99.8%		98.8% 97.1%			99.6% 99.4%		99.4% 99.0%	99.9% 99.7%												



Table 13 Emissions and fuel consumption results from the Fiat Tipo 1.4 vehicle over the constant speed cycle for TWC Low S

			Development Inst	itute Ltd					F	-			-		nstant : 80 km	-	•			
VIN: ZFA35	600006K202	52			Vehicle	model:					Fiat	Tipo 1.4	LPG	τ.	res:	Continents	al ContiEco	Contact E 2	25/45 017	
														iy	163.	Continente		Contact 0 2	23/43 111	V AL
Inertia [kg]:		1509		F	Phase 1 - 80	km/h in 5t	h gear (hot	stabilised)		Phase 2 - 8	80 km/h in 5	5th gear (ho	t stabilised	I)	CO ₂ er	mission	Fuel con	sumption	
Mileage		Chassis				[mg/l	(m]					[mg	/km]			[g/I	km]	[l/100	km] ⁽²⁾	Note 1
[km]	Date	dyno F0/F1/F2	Test No.	THC	NMHC	со	NOx	PM	PN	THC	NMHC	со	NOx	PM	PN	P1	P2	P1	P2	
Ageing stage	e: 0 cycles	1	1	BAG - MOD	AL DIL - PRE	- POST					,	,								
		45.1		0	0	21	0	0.06	3.88E+08	0	0	27	0	0.14	3.63E+08	103.7	100.5	6.38	6.18	Bags
4 264	23.10.2018	-0.87	L1-0471	0	0	21	0		-	0	0	27	0	-	-	103.9	100.6	6.39	6.19	Modal Dil
4 264	23.10.2018	0.0390	L1-0471	304	289	3002	2240	-	-	293	278	2963	2142	-	-	100.3	97.1	6.52	6.31	Modal PRE cat
				0	0	21	0	-	-	0	0	27	0	-	-	105.9	102.6	6.52	6.31	Modal TP
	<i>T</i> v	VC effective	ness <u>per phase</u>	99.84%	99.88%	99.31%	99.99%	-	-	99.86%	99.91%	99.08%	100.00%	-	-					
Mean TV	VC effectiven	ess (mean o	f <u>both phases</u>)	99.85%	99.89%	99.19%	99.99%	-	-	-	-	-	-	-	-					
Max. T	WC effective	ness (max. o	f <u>both phases</u>)	99.86%	99.91%	99.31%	100.00%	-	-	-	-	-	-	-	-					
Min. T	WC effective	ness (min. o	f <u>both phases</u>)	99.84%	99.88%	99.08%	99.99%	-	-	-	-	-	-	-	-					
Ageing stage	e: 250 cycles			BAG - MOD	AL DIL - PRE	- POST														
		45.1		0	0	23	0	0.00	1.68E+08	0	0	21	0	0.02	2.51E+08	102.4	101.7	6.30	6.26	Bags
5 131	19.03.2019	-0.87	L1-0156	1	0	23	0	-	-	1	0	21	0	-	-	98.7	98.2	6.31	6.27	Modal Dil
	10.00.2010	0.0390	2. 5150	272	259	3006	2167	-	-	275	261	3001	2150	-		104.6	103.9	6.41	6.38	Modal PRE cat
L				0	0	26	0	-	-	0	0	24	0	-	-	102.6	101.9	6.44	6.39	Modal TP
L			ness <u>per phase</u>		99.96%	99.13%	100.00%		-	100.00%	99.98%	99.19%	100.00%	-	-					
			f <u>both phases</u>)	100.00%	99.97%	99.16%	100.00%	-	-	-	-	-	-	-	-					
			f <u>both phases</u>)	100.00%	99.98%	99.19%	100.00%	-	-	-	-	-	-	-	-					
Min. 7	WC effective	ness (min. o	f <u>both phases</u>)	100.00%	99.96%	99.13%	100.00%	-	-	-	-	-	-	-	-					



| BOS | MAL Automotiv | Ive R&D Institut | te Ltd | | | | |
 |
 | | | |
 | NEDC t | test (UN | ECE R83 | 3) - NEDC | driving
 | cycle | |
 | |
 | | | | | | |
|-------------|------------------------------|--|----------|---|---|--|--
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--	--	---	--
---|--|---|---
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---|---|---|--|---
---|---|--|---|
| VIN: ZFA3 | 35600006K20 | 0252 | | Model: | | | Vehicle | e model:
 | Fiat Tipo
 | 1.4 LPC | 3 | |
 | | | Er | nission s | tandard:
 | Euro 6 | |
 | | Ту
 | res: | Continent | al ContiEcc | Contact 5 2 | 225/45 R17 | V XL |
| Inertia [kg |] 1360 | | | | | | sions in | the NED
 | C test
 | | | |
 | Emissions | | C phase | |
 | | s in the EU | DC phase
 | | c
 | O2 emissio | ins | Fu | el consump | |] |
| Mieage | Date | Chassis
dvno | Test No. | | cO | | THC | NMHC
 | Emission
 | NOx | PM | PN | THC
 | Emis
NMHC | ssions meas | ared NOx | PN | THC
 | Emi | co | NOx
 | PN |
 | [9/km] | 1 | | [l/100 km] (** | 1 | Note 1 |
| [km] | | F0/F1/F2 | | [# | ng/km] | 1 | |
 |
 | ş/km] | | 1 | |
 | | [mg/km] | | |
 | | [mg/km] |
 | | NEDC
 | UDC | EUDC | NEDC | UDC | EUDC | |
| Ageing sta | ge: 0 cycles | 21.0 | | BAG - MODAL DIL - 1 | PRE - POST
846 | 1 45 | 56 | 51
 | 564
 | 10 | 0.54 | 4.32E+11 | 151
 | 137 | 1449 | - 22 | 1.14E+12 |
 | 0 | 46 | 2
 | 1.57E+10 | 161.4
 | 223.1 | 125.3 | 9.99 | 13.89 | 7.71 | Baos |
| | | -1.13 | | 73 66 | 846 | 15 | 57 | 52
 | 559
 | 9 | 0.54 | 4.32E+11 | 151
 | 137 | 1449 | 22 | 1.14E+12 | 0
 | 0 | 40 | 2
 | 1.5/E+10 | 161.4
 | 223.1 | 125.3 | 10.02 | 13.89 | | Modal Dil |
| 4 061 | 27.09.2018 | 3 0.0401 | L1-0435 | | | | 702 | 667
 | 7054
 | 2376 | - | - | 1149
 | 1087 | 11534 | 1875 | - | 441
 | 421 | 4434 | 2669
 | - | 153.4
 | 210.4 | 120.1 | 10.25 | 14.27 | 7.90 | Modal PRE cat |
| | | _ | | TWO | C effectiven | ess (pre-bag) | 70
92.1% | 63
92.4%
 | 601
92.0%
 | 11 99.6% | - | - | 188
86.9%
 | 169
87.4% | 1528
87.4% | 26 | - | 0
99.9%
 | 0
99.9% | 59
99.0% | 2
99.9%
 | | 165.1
 | 227.4 | 128.7 | 10.22 | 14.17 | 7.92 | Modal TP
TWC eff |
| | | | | | | ess (pre-post) | 90.1% | 90.6%
 | 91.5%
 | 99.5% | - | - | 83.6%
 | 84.4% | 86.8% | 98.6% | | 99.9%
 | 99.9% | 98.7% | 99.9%
 | - |
 | | | | | | TWC eff |
| | | 21.0 | | 63 57 | 634 | 14 | 48 | 44
 | 423
 | 9 | 0.67 | 4.34E+11 | 131
 | 119 | 1059 | 18 | 1.13E+12 | 0
 | 0 | 50 | 3
 | 2.41E+10 | 161.9
 | 221.9 | 126.8 | 10.01 | 13.77 | 7.80 | Bags |
| 4 083 | 03.10.2018 | -1.13 | L1-0437 | | - | - | 49
675 | 45
 | 423
7330
 | 8
2354 | - | - | 134
1065
 | 122
1009 | 1056
12085 | 18 | - | 0
 | 0
426 | 52
4547 | 3 2640
 | - | 162.4
153.2
 | 222.3
208.4 | 127.4
120.9 | 10.04 | 13.80 | 7.84 | Modal Dil
Modal PRE cat |
| | | 0.0401 | | | | 1 | 58 | 53
 | 449
 | 10 | - | - | 156
 | 142 | 1110 | 22 | - | 0
 | 0 | 62 | 3
 | | 165.6
 | 226.6 | 129.9 | 10.25 | 14.10 | 8.00 | Modal TP |
| | | | | | | ess (pre-bag) | 92.8% |
 |
 | 99.6% | | | 87.7%
 | 88.2% | 91.2% | 99.0% | | 100.0%
 | 100.0% | 98.9% | 99.9%
 | |
 | | | | | | TWC eff |
| | 1 | 21.0 | 1 | 61 56 | effectivene
522 | ss (pre-post) | 91.4% | 91.8%
43
 | 93.9%
348
 | 99.6%
10 | 0.29 | 2.93E+11 | 85.3%
128
 | 86.0% | 90.8%
858 | 98.8% | 7.67E+11 | 100.0%
 | 99.9% | 98.6%
52 | 99.9%
 | 1.95E+10 | 160.5
 | 223.0 | 124.3 | 9.91 | 13.82 | 7.65 | TWC eff
Bags |
| 4 209 | 16.10.2018 | 4.42 | L1-0450 | | | | 48 | 40
 | 347
 | 10 | - | - | 129
 | 118 | 854 | 20 | - | 0
 | 0 | 54 | 4
 | - | 161.0
 | 223.3 | 125.0 | 9.95 | 13.84 | 7.70 | Modal Dil |
| + 200 | 10.10.2018 | ⁵ 0.0401 | L1-0400 | | | | 648 | 617
 | 7044
 | 2309 | - | - | 1058
 | 1005 | 11622 | 1767 | | 411
 | 393 | 4396 | 2623
 | | 151.9
 | 208.8 | 119.0 | 10.14 | 14.16 | | Modal PRE cat |
| | | | | TW | Coffectiven | ess (pre-bag) | 52
92.7% | 48
93.0%
 | 353
95.1%
 | 11
99.6% | | | 143
87.9%
 | 130
88.4% | 854
92.6% | 23
98.9% | | 0
99.9%
 | 0
99.9% | 63
98.8% | 4 99.9%
 | | 164.1
 | 227.5 | 127.5 | 10.14 | 14.10 | 7.85 | Modal TP
TWC eff |
| | | | | | | ess (pre-bag)
ss (pre-post) | 91.9% | 92.3%
 | 95.0%
 | 99.5% | - | - | 86.5%
 | 87.1% | 92.7% | 98.7% | - | 100.0%
 | 99.9% | 98.6% | 99.9%
 | • | 1
 | | | | | | TWC eff |
| | - | | | | | | 50
52 | 46
47
 | 445
443
 | 9 | 0.50 | 3.87E+11 | 136
 | 124 | 1122 | 20 | 1.02E+12 | 0
 | 0 | 50
51 | 3
 | 1.97E+10 | 161.3
161.8
 | 222.7 | 125.5 | 9.97 | 13.83
13.84 | 7.72 | Bags
Modal Dil |
| | | | | Mea | n values | | 52
675 | 47
642
 | 443
7143
 | 9
2346 | | | 139
 | 127 | 1114 | 20 | | 0
433
 | 0
413 | 51
4459 | 3
2644
 | | 161.8
 | 222.9 | 126.2 | 10.00 | 13.84 | 7.76 | Modal Dil
Modal PRE cat |
| | | | | | | | 60 | 54
 | 468
 | 11 | - | - | 162
 | 147 | 1164 | 23 | | 0
 | 0 | 61 | 3
 | | 164.9
 | 227.2 | 128.7 | 10.20 | 14.11 | 7.92 | Modal TP |
| | | | | | | | 3.9 | 3.4
 | 89.7
 | 0.5 | 0.16 | 6.59E+10 | 10.2
 | 8.9 | 245.2 | 1.6 | 1.76E+11 | 0.1
 | 0.1 | 2.5 | 0.5
 | 3.43E+09 | 0.58
 | 0.55 | 1.01 | 0.04 | 0.05 | 0.06 | Bags |
| | | | | Standar | d deviation | n | 4.2 | 3.6
 | 87.8
132.6
 | 0.5
27.8 | | | 11.2
41.3
 | 9.7
37.5 | 240.0 | 1.6 | | 0.1
 | 0.1 | 2.4 | 0.5
 | | 0.57
 | 0.39 | 0.95 | 0.04 | 0.03 | 0.06 | Modal Dil
Modal PRE cat |
| | | | | | | | 7.2 | 6.3
 | 102.2
 | 0.5 | - | | 19.2
 | 16.7 | 277.9 | 1.5 | - | 0.0
 | 0.0 | 1.9 | 0.6
 | | 0.62
 | 0.37 | 0.99 | 0.04 | 0.04 | 0.06 | Modal TP |
| | | | | | | | 2.2 | 2.0
 | 51.8
 | 0.3 | 0.09 | 3.80E+10 | 5.9
 | 5.1 | 141.6 | 0.9 | 1.01E+11 | 0.1
 | 0.1 | 1.5 | 0.3
 | 1.98E+09 | 0.34
 | 0.32 | 0.58 | 0.02 | 0.03 | 0.04 | Bags |
| | | | | Type A | uncertainty | v | 2.5
12.8 | 2.1
 | 50.7
76.5
 | 0.3 | - | - | 6.5
23.9
 | 5.6
21.7 | 138.5
139.5 | 0.9
28.1 | - | 0.1
8.9
 | 0.1 | 1.4 | 0.3
 | - | 0.33
 | 0.23 | 0.55 | 0.02 | 0.02 | 0.03 | Modal Dil
Modal PRE cat |
| | | | | | | | 4.2 | 3.6
 | 59.0
 | 0.3 | - | - | 11.1
 | 9.6 | 160.5 | 0.9 | - | 0.0
 | 0.0 | 1.1 | 0.3
 | | 0.36
 | 0.22 | 0.57 | 0.03 | 0.02 | | Modal TP |
| | | | | Mean TWC effe
Max. TWC effe | ctiveness (| pre-bag) | 92.6% |
 |
 | 99.6% | | | 87.5%
 | 88.0%
88.4% | 90.4% | 98.9% | | 99.9%
100.0%
 | 99.9% | 98.9% | 99.9%
 | |
 | | | | | | |
| | | | | Min. TWC effe | tiveness (p | pre-bag) | 92.8% |
 |
 | | | | |
 | | | | |
 | | |
 | |
 | | | | | | |
| | | | | | | | | 92.4%
 | 92.0%
 | 99.6% | - | 1 - | 86.9%
 | 87.4% | 87.4% | 98.8% | | 99.9%
 | 99.9% | 98.8% | 99.9%
 | |
 | | | | | | |
| | | | | Mean TWC effe | ctiveness (p | pre-post) | 91.1% | 91.6%
 | 93.4%
 | 99.6% | - | - | 85.1%
 | 85.8% | 90.1% | 98.8%
98.7% | - | 99.9%
100.0%
 | 99.9%
99.9% | 98.8%
98.6% | 99.9%
99.9%
 | - |
 | | | | | | |
| Ageing sta | | | | Mean TWC effe
Max. TWC effect | ctiveness (p | pre-post)
pre-post) | 91.1%
91.9% | 91.6%
92.3%
 | 93.4%
95.0%
 | 99.6%
99.6% | | - | 85.1%
86.5%
 | 85.8%
87.1% | 90.1%
92.7% | 98.8%
98.7%
98.8% | -
- | 99.9%
100.0%
100.0%
 | 99.9%
99.9%
99.9% | 98.8%
98.6%
98.7% | 99.9%
99.9%
99.9%
 | |
 | | | | | | |
| | ige: 250 cycle: | 25 | | Mean TWC effe | ctiveness (p
tiveness (p
tiveness (p | pre-post)
pre-post)
pre-post) | 91.1% | 91.6%
92.3%
 | 93.4%
95.0%
91.5%
 | 99.6% | | | 85.1%
 | 85.8% | 90.1% | 98.8%
98.7% | -
- | 99.9%
100.0%
 | 99.9%
99.9% | 98.8%
98.6% | 99.9%
99.9%
 | |
 | | | | | | |
| | | 21.0 | | Mean TWC effe
Max. TWC effec
Min. TWC effec | ctiveness (p
tiveness (p
tiveness (p | pre-post)
pre-post)
pre-post) | 91.1%
91.9%
90.1%
47 | 91.6%
92.3%
90.6%
 | 93.4%
95.0%
91.5%
400
 | 99.6%
99.6%
99.5%
18 | | 2.13E+11 | 85.1%
86.5%
83.6%
 | 85.8%
87.1%
84.4% | 90.1%
92.7%
86.8%
1029 | 98.8%
98.7%
98.8%
98.6% | -
- | 99.9%
100.0%
100.0%
 | 99.9%
99.9%
99.9%
99.9% | 98.8%
98.6%
98.7%
98.6%
34 | 99.9%
99.9%
99.9%
99.9%
2
 | | 159.6
 | 220.3 | 124.2 | 9.86 | 13.67 | 7.64 | Bags |
| 5 865 | ge: 250 cycle:
03.01.2020 | 21.0 | L1-0002 | Mean TWC effe
Max. TWC effec
Min. TWC effec | ctiveness (p
tiveness (p
tiveness (p | pre-post)
pre-post)
pre-post) | 91.1%
91.9%
90.1%
47
49 | 91.6%
92.3%
90.6%
43
44
 | 93.4%
95.0%
91.5%
 | 99.6%
99.6%
99.5% | - | 2.13E+11 | 85.1%
86.5%
83.6%
127
130
 | 85.8%
87.1%
84.4%
115
117 | 90.1%
92.7%
86.8%
1029
1022 | 98.8%
98.7%
98.8%
98.6%
44
43 | -
-
- | 99.9%
100.0%
100.0%
 | 99.9%
99.9%
99.9%
99.9%
1
1 | 98.8%
98.6%
98.7%
98.6% | 99.9%
99.9%
99.9%
99.9%
2
2
 | - | 160.3
 | 221.6 | 124.7 | 9.91 | 13.75 | 7.67 | Bags
Modal Dil
Modal PRE cat |
| 5 865 | | 21.0 | L1-0002 | Mean TWC effe
Max. TWC effec
Min. TWC effec
BAG - MODAL DIL - I | ctiveness (p
tiveness (p
tiveness (p
PRE - POST | pre-post)
pre-post)
pre-post) | 91.1%
91.9%
90.1%
47
49
529
49 | 91.6%
92.3%
90.6%
43
44
501
44
 | 93.4%
95.0%
91.5%
400
398
6813
334
 | 99.6%
99.6%
99.5%
18
18
2350
19 | -
-
-
-
-
- | 2.13E+11 | 85.1%
86.5%
83.6%
127
130
819
133
 | 85.8%
87.1%
84.4%
115
117
773
119 | 90.1%
92.7%
86.8%
1029
1022
10789
841 | 98.8%
98.7%
98.8%
98.6%
44
43
1902
46 | 5.76E+111 | 99.9%
100.0%
99.9%
1
1
359
0
 | 99.9%
99.9%
99.9%
1
1
342
0 | 98.8%
98.6%
98.7%
98.6%
34
35
4498
38 | 99.9%
99.9%
99.9%
99.9%
2
2
2627
3
 | 2.00E+09 |
 | | | | | | Modal Dil
Modal PRE cat
Modal TP |
| 5 865 | | 21.0 | L1-0002 | Mean TWC effe
Max. TWC effec
Min. TWC effec
BAG - MODAL DIL - I | ctiveness (p
tiveness (p
PRE - POST | pre-post)
pre-post)
pre-post) | 91.1%
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47
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49
91.1% | 91.6%
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44
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398
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94.1%
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18
18
2360
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99.3% | -
-
-
-
- | 2.13E+11 | 85.1%
86.5%
83.6%
127
130
819
133
84.5%
 | 85.8%
87.1%
84.4%
115
117
773
119
85.2% | 90.1%
92.7%
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1029
1022
10789
841
90.5% | 98.8%
98.7%
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44
43
1902
46
97.7% | 5.76E+111
-
- | 99.9%
100.0%
99.9%
1
1
359
0
99.8%
 | 99.9%
99.9%
99.9%
1
1
342
0
99.8% | 98.8%
98.6%
98.7%
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34
35
4498
38
99.3% | 99.9%
99.9%
99.9%
99.9%
2
2
2627
3
99.9%
 | 2.00E+09 | 160.3
153.1
 | 221.6
206.7 | 124.7
121.9 | 9.91
10.17 | 13.75
13.91 | 7.67
8.00 | Modal Dil
Modal PRE cat
Modal TP
TWC eff |
| 5 865 | | 21.0 | L1-0002 | Mean TWC effe
Max. TWC effec
Min. TWC effec
BAG - MODAL DIL - I | ctiveness (p
tiveness (p
PRE - POST | pre-post)
pre-post)
pre-post) | 91.1%
91.9%
90.1%
47
49
529
49 | 91.6%
92.3%
90.6%
43
44
501
44
91.5%
 | 93.4%
95.0%
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400
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18
18
2350
19 | -
-
-
-
- | 2.13E+11
-
-
-
-
-
-
-
-
-
-
-
-
-
-
-
-
-
- | 85.1%
86.5%
83.6%
127
130
819
133
 | 85.8%
87.1%
84.4%
115
117
773
119 | 90.1%
92.7%
86.8%
1029
1022
10789
841 | 98.8%
98.7%
98.8%
98.6%
44
43
1902
46 | 5.76E+111
-
- | 99.9%
100.0%
99.9%
1
1
359
0
 | 99.9%
99.9%
99.9%
1
1
342
0 | 98.8%
98.6%
98.7%
98.6%
34
35
4498
38 | 99.9%
99.9%
99.9%
99.9%
2
2
2627
3
 | 2.00E+09 | 160.3
153.1
 | 221.6
206.7 | 124.7
121.9 | 9.91
10.17 | 13.75
13.91 | 7.67
8.00 | Modal Dil
Modal PRE cat
Modal TP |
| 5 865 | 03.01.2020 | 21.0
-1.13
0.0401
21.0
-1.13 | | Mean TWC effe
Max. TWC effec
Min. TWC effec
BAG - MODAL DIL - I | ctiveness (p
tiveness (p
PRE - POST | pre-post)
pre-post)
pre-post) | 91.1%
91.9%
90.1%
47
49
529
49
91.1%
90.7%
62
63 | 91.6%
92.3%
90.6%
43
44
501
44
91.5%
91.2%
55
56
 | 93.4%
95.0%
91.5%
400
398
6813
334
94.1%
95.1%
642
649
 | 99.6%
99.6%
99.5%
18
2360
19
99.3%
99.2%
16
16 | 0.27 | | 85.1%
86.5%
83.6%
127
130
819
133
84.5%
83.7%
165
169
 | 85.8%
87.1%
84.4%
115
117
773
119
85.2%
84.6%
148
152 | 90.1%
92.7%
86.8%
1029
1022
10789
841
90.5%
92.2%
1672
1688 | 98.8%
98.7%
98.8%
98.6%
44
43
1902
46
97.7%
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13.71
13.33
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13.39
13.39
13.47
13.25
13.61
13.70
13.90
13.90
13.95
13.64
13.64
13.76
13.64
13.76
13.64
0.15
0.20
0.20
0.09
0.02 | 7.67
8.00
8.00
7.47
7.50
7.62
7.82
7.83
7.55
7.75
7.55
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7.71
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Table 14 Emissions and fuel consumption results from the Fiat Tipo 1.4 vehicle over the NEDC cycle for TWC High S

 THC
 NMHC
 CO
 NOx

 Euro 6 SI limits [mg/km]
 100
 68
 1000
 60

(*) - as defined in Regulation (EC) 2007/595, applied only at the 0 cycle ageing stage (for informational purposes)



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Table 15Emissions and fuel consumption results from the Fiat Tipo 1.4 vehicle over theWLTC cycle for TWC High S at 0 cycles

	Automotive	Research and Dev Emissions Testing I	velopment Ins	ititute Ltd															WLT	P test (Reg 2()17/115	1) - WLTC d	riving	cycle														
/IN: ZFA356	00006K2	0252			Vehic	le mode	I:				Fiat	Tipo 1.4	LPG							E	nission s	tandard:	Euro 6							Ту	res:			Contine	tal ContiEcoC	ontact 5 225/4	5 R17 V XL		
nertia [kg]:		1509				Emis	sion WLTC					Emission LC	W			Em	ission MID	DLE			E	mission HIG	н		E	mission Ex-H	IIGH			(CO, emissie	n			F	lel consum	tion		
1 01		Chassis dyna	-				mg/km]					[mg/km]					[mg/km]					[mg/km]				[mg/km]					[g/km]					[V100 km] (2			Note 1
/lileage[km]	Date	F0/F1/F2	Test No.	THC	NMHC	co	NOx	PM	PN	THC	NMHC	co	NOx	PN	THC	NMHC	со	NOx	PN	THC	NMHC	co	NOx PN	THC	NMHC	co	NOx	PN	WLTC	LOW	MIDDLE	HIGH	Ex-HIGH	WLTC	LOW	MIDDLE	HIGH	Ex-HIGH	1
			-		DAL DIL - PR	1	1	1	1				1			1																							
lgeing stage	. u cycles	45.1	-	57 BAG - MO	53	404	26	1.21	6.17E+11	426	394	2229	26	4.19E+12	0	0	181	4	1.37E+11	0	0	128	5 2.82E+1	1	1	90	54	6.54E+10	148.6	215.7	145.1	128.7	142.7	9.19	13.56	8.94	7.93	8.78	Bags
		0.97		59	55	404	26	1.21	0.172+11	420	409	2198	30	4.100+12	1	0	181	4	1.3/E+11	0	0	128	5 -	1	1	89	53	3.04E+10	148.0	216.3	145.1	128.0	142.7	9.19	13.60	8.94	7.93	8.78	Modal Dil
4 094	2018-10-	-04 0.0390	L1-0438	717	687	6992	2473		1	1665	1594	13826	1390		778	748	8354	1812		568	545	5706	2272 -	458	436	4769	3432		139.0	199.9	129.4	119.3	138.8	9.22	13.94	8.91	7.92	9.08	Modal PRE cat
		0.0000		65	60	424	27			490	451	2234	42		0	0	190	5		0	0	151	4 .	0		120	54		152.1	220.7	147.8		147.0	9.41	13.88			9.05	Modal TP
		TWC effectivene	ss (pre-bag)					1% -	-	74.4				6 -	100.0%			99.8%		100.0%				99.95				6 -											TWC eff
		TWC effectivenes		90.99						70.6					100.0%					100.0%				99.95															TWC eff
		45.1	1	47	43	515	10		6.01E+11	353	323	2315	40	4.11E+12	1	0	327		4.27E+10	0	0	428	6 8.40E+0		1	25		1.22E+11	150.1	218.8	146.9	129.1	144.4	9.29	13.75	9.07	7.98	8.88	Bags
4 117		-0.87		50	45	510	10			367	336	2303	36		1	1	325	3		1	1	420	6 -	1	1	26	7	-	150.8	219.2	146.9	129.3	146.0	9.33	13.77	9.06	7.99	8.98	Modal Dil
4 117	2018-10-	0.0390	L1-0441	700	669	7609	2436		-	1573	1499	15241	1314		759	726	9532	1836		584	560	6597	2152 -	442	421	4531	3444		139.7	201.4	130.6	118.2	140.4	9.46	14.15	9.10	8.02	9.16	Modal PRE cat
				56	51	515	11	-	-	417	379	2240	43		1	1	339	3		0	0	441	5 -	0	1	35	9	-	153.8	223.6	149.7	131.9	148.9	9.52	14.04	9.24	8.15	9.16	Modal TP
		TWC effectivene	ess (pre-bag)	93.29	6 93.5%	93.2	% 99.6	- %	-	77.5	% 78.5	% 84.8	6 97.09	6 -	99.9%	99.9%	96.6%	99.9%		99.9%	99.9%	93.5%	99.7% -	99.95	% 99.89	6 99.49	99.89	6 -											TWC eff
		TWC effectivenes	ss (pre-post)	92.09	6 92.4%	93.2	% 99.6	- %	-	73.5	% 74.7	% 85.3	6 96.79	6 -	99.9%	99.9%	96.4%	99.9%		100.0%	99.9%	93.3%	99.8% -	99.95	% 99.89	6 99.29	99.79	6 -											TWC eff
		45.1		43	39	392	11	0.68	5.32E+11	317	289	2284	49	3.65E+12	1	0	189	10	5.47E+10	0	0	109	4 1.51E+1	1	1	46	3	8.98E+10	151.7	222.6	147.3		146.3	9.38	13.97	9.07	8.04		Bags
4 131	2018-10-	-0.87	L1-0458	44	40	393	10	-		330	300	2287	46	-	1	1	191	10		1	0	111	4 -	1	0	46	3	-	152.5	224.1	147.2	130.9	147.6	9.43	14.07	9.07	8.06	9.08	Modal Dil
4131	2010-10-	0.0390	L1-0400	592	563	6830	2534		-	1318	1249		1457	-	613	585	7620	1911		468	446	5676	2317 -	417		4848	3483	-	144.2	211.1	135.0	122.7	143.0	9.64	14.54	9.15		9.34	Modal PRE cat
				49	45	400	11	-		371	336	2285	52		0	0	206	10		0	0	112	4 -	0	0	57	4	-	155.5	228.5	150.0	133.4	150.6	9.61	14.34	9.24	8.22	9.27	Modal TP
		TWC effectivene		92.89						75.9					99.9%					99.9%				99.95															TWC eff
		TWC effectivenes	ss (pre-post)							71.9					99.9%					100.0%				100.05	% 99.9%														TWC eff
				49	45	437	16	0.97	5.83E+11	366	335	2276	42	3.99E+12	1	0	232	6	7.82E+10	0	0	222	5 1.72E+1		1	54	22	9.24E+10	150.1	219.0	146.4	129.4	144.4	9.28	13.76	9.03		8.89	Bags
	Me	an values		51	47	434	15			380	348	2263	39		1	1	232	6	-	1	0	220	5 -	1	1	54	21		150.8	219.9	146.3	129.6	145.9	9.32	13.81	9.02	7.99	8.98	Modal Dil
				670	640	7144	2481			1519	1447		1387		717	686	8502	1853		540	517	5993	2247 -	439	418	4716	3453		140.9	204.1	131.7	120.1	140.7	9.48	14.21	9.05	8.06	9.19	Modal PRE cat
				57	52	446	16	- 0.00	2.000 10	426	389	2253	46	2.405.111	0	0	245	6	4.045.10	0.1	0	235	4 -	0	1	70	22	0.0001.00	153.8	224.3	149.2	132.2	148.8	9.51	14.09	9.20	8.15	9.16	Modal TP
				5.9 6.1	5.8 6.1	55.3	7.4	0.22	3.68E+10	44.9	43.7	35.4	5.4	2.40E+11	0.2	0.1	67.2 65.8	3.3	4.21E+10	0.1	0.1	145.9	0.7 8.21E+0	0.0	0.0	27.0	23.0	2.32E+10	1.30	2.80	0.94	0.78	1.48	0.08	0.17	0.06	0.04	0.09	Bags Modal Dil
	Standa	ard deviation		6.1 55.5	54.6	53.8 335.6	40.5			46.5	45.4		58.6		0.2 73.9	0.1	65.8	3.1	· · ·	0.1 51.3	0.2	427.2	69.3 -	0.0		26.4	22.7		2.29	3.20	1.00	0.93	1.45	0.08	0.19	0.06	0.06	0.09	Modal Dil Modal PRE cat
				6.5	6.3	49.4	7.4	1		49.1	47.2		4.3		0.2	0.1	67.0	42.1		0.1	0.1	427.2	0.6 -	0.1	0.1	36.0	22.0		1.39	3.22	1.00	0.92	1.45	0.12	0.25	0.10	0.09	0.09	Modal PRE cat Modal TP
				3.4	3.4	31.9	4.3		2.13E+10	25.9	25.3		3.1	1.38E+11	0.2	0.0	38.8		2.43E+10	0.1	0.1	84.3	0.4 4.74E+0		0.0	15.6		1.34E+10	0.75	1.62	0.55	0.92	0.85	0.05	0.10	0.04	0.03	0.05	Bags
				3.5		31.1	4.3	0.10		26.8		26.8	2.9		0.1	0.0	38.0	1.8		0.1	0.1		0.4 -	0.0	0.1	15.2	13.1		0.81	1.85	0.58	0.54	0.83	0.05	0.10	0.04	0.03	0.05	Modal Dil
	Type A	A uncertainty		32.0	31.5	193.8	23.4			84.8	84.2		33.8		42.6	41.7	454.8	24.3		29.6	29.2	246.6	40.0 -	9.7	9.5	77.9	12.7		1.32	2.86	1.38	1.12	0.99	0.00	0.14	0.06	0.05	0.06	Modal PRE cat
				3.8	3.6	28.5	4.3			28.4	27.3		2.5		0.1	0.0	38.7	1.8		0.1	0.1	84.8	0.4 -	0.1	0.1	20.8	12.9		0.80	1.86	0.58	0.53	0.83	0.05	0.11		0.03	0.05	Modal TP
Mea	TWC eff	fectiveness (pre-	bag)	92.79				- %		76.0		% 84.0		6 -	99.9%					99.9%				99.95				6 -											
				93.29						77.5					100.0%				-	100.0%	100.0%			99.95															
Max	TWC effe	ectiveness (pre-l	bag)															+					99.7% -	99.95	% 99.89	6 98.19	98.49	/	i i										
		ectiveness (pre-l ectiveness (pre-l		92.19			% 98.9	- 1%	-	74.4	% 75.3	% 83.2	6 96.6%	6 -	99.9%	99.9%	96.6%	99.5%		99.9%	99.9%	93.5%																	
Min	TWC effe		bag)		6 92.3%	93.2			-	74.4					99.9% 99.9%					99.9%				99.95															
Min Mear	TWC effe	ectiveness (pre-t	bag) post)	92.19	6 92.3% 6 91.9%	93.2 93.8	% 99.3	- 1%			% 73.2	% 84.1	6 96.7%	6 -		99.9%	97.2%	99.7%			99.9%	96.2%	99.8% -		% 99.9%	6 98.59	99.49	6 -											



Table 16 Emissions and fuel consumption results from the Fiat Tipo 1.4 vehicle over the WLTC cycle for TWC High S at 50 cycles

BOSMAL A	stomotive Res	SAAA search and Deve ssions Testing L	elopment Ins	Stute Ltd														WLTI	P test (I	Reg 20	17/115	1) - WL	.TC driv	ving cy	cle														
'IN: ZFA3560	0006K2025	2			Vehic	le model					Fiat 1	"ipo 1.4 L	PG						En	nission st	andard:	Euro 6								Tyre	s:			Contine	ntal ContiEcol	Contact 5 225/4	5 R17 V XL		
nertia [kg]:		1509				Emissi	on WLTC				Er	nission LOV	/		E	mission MIDI	DLE			En	ission HIG	н			Emis	sion Ex-HIGH	H			C	O ₂ emissior	n			F	uel consump			
ileage[km]	Date	Chassis dyno	Test No.			n]	g/km]		· · · · · · · · · · · · · · · · · · ·			[mg/km]				[mg/km]					[mg/km]					[mg/km]					[g/km]					[V100 km] (2	5		Note 1
neage(km)	Date	F0/F1/F2	Test NO.	THC	NMHC	co	NOx	PM	PN	THC	NMHC	co	NOx PN	THC	NMHC	co	NOx	PN	THC	NMHC	co	NOx	PN	THC	NMHC	co	NOx	PN	WLTC	LOW	MIDDLE	HIGH	Ex-HIGH	WLTC	LOW	MIDDLE	HIGH	Ex-HIGH	1
geing stage:	50 cycles			BAG - MOD	AL DIL - PRI	E - POST																																	
		45.1		62	57	692	14	0.50	5.30E+11	463	425		84 3.76E+12		1	223		3.49E+10	0	0	438		9.77E+09	1	1	67	3 (215.9	142.4	124.8		9.12	13.72		7.72		Bags
5 373	11.06.2019	-0.87	L1-0291	65	60	695	13	· · ·		483	445	3680	78 -	2	1	226	6		1	1	441	3		1	1	69	3			216.4	142.5	125.0	144.0	9.15	13.76		7.73		Modal Dil
		0.0390		648 77	619 71	8118 769	2252			1548 575	1470 528	17843 4090	1171 - 89 -	675	647	9512 257	1569		520 0	499	7026	1895	-	407	389	4627	3360	-	134.5	197.0	126.2 145.3	111.5 127.5	136.0	9.18 9.34	14.12	8.81	7.63	8.88	Modal PRE ci Modal TP
	714	C effectivenes	a (are here)	90.4%				-		70.1%				99.89	1 1				99.9%	1 1	93.8%		-	99.8%	99.8%	98.5%	2 99.9%		150.5	221.0	140.3	127.5	147.0	9.34	14.09	6.90	7.89	9.05	TWC eff
		C effectivenes		90.4%						62.9%				99.87					99.9%		93.8%			99.8%	99.8%	98.5%	99.9%												TWC eff
		45.1	1	57	52	506	14		5.20E+11	425	389	3267	82 3.51E+12		1	109		4.54E+10	0	0	109		2.04E+10	1	1	51		1.12E+11	147.3	214.8	144.4	126.6	141.8	9.12	13.61	8.89	7.80	8.72	Bags
		-0.87		59	54	509	13			443	406	3275	80 -	2	1	111	6		1	0	110	2	-	1	1	53	3		148.2	215.8	145.2	127.3	142.9	9.18	13.67	8.94	7.84	8.80	Modal Dil
5 397	12.06.2019	0.0390	L2-0294	628	600	7573	2333		-	1425	1350	16771	1315 -	678	651	8846	1664	-	511	491	6353	2046	-	403	385	4469	3346	-	135.8	198.0	129.6	114.8	134.5	9.20	14.07	8.95	7.77	8.78	Modal PRE c
				73	67	565	15	-		550	505	3716	93 -	1	1	112	5	-	0	0	99	2	-	1	1	57	2		151.2	220.3	148.0	129.8	145.9	9.37	14.01	9.11	7.99	8.98	Modal TP
		C effectivenes		91.0%						70.2%				99.99					99.9%		98.3%			99.8%	99.8%	98.8%	99.9%												TWC eff
	TW	C effectivenes:	s (pre-post)	88.3%					1.1	61.4%				99.99	6 99.99				99.9%	99.9%	98.4%			99.8%	99.8%	98.7%	99.9%								_				TWC eff
		45.1		52	48	494	14	0.50	5.63E+11	392	358	2955	86 3.98E+12	1	1	249		4.27E+10	0	0	127	3	2.22E+10	1	1	32	3 1	5.47E+10		218.0	145.3	126.6		9.15	13.77				Bags
5 443	13.06.2019	-0.87	L1-0299	55 600	50	493 7695	14 2315	· ·		408	373	2942	83 -	2 644	615	250	3		1 469	1 448	130 6388	3		396	1 379	33 4397	3 3311	-		218.8	145.9	126.8		9.20	13.82		7.81	8.78	Modal Dil Modal PRE ci
		0.0390		71	572 65	7695	2315			533	489	16529 3382	91 -	044	615	9650 274	1603		409	448	138	2086	-	390	3/9	439/	3311			201.4	129.9	115.3 129.4		9.25 9.39	14.24		7.79	8.78	Modal PRE C
	TIA	C effectivenes	re (pro-bag)	91.3%				· ·	-	71.7%				99.99	1 1				99.9%	v 1	98.0%	2 99.9%		99.9%	99.8%	37 99.3%	3 99.9%		151.0	223.3	148.7	129.4	145.7	9.39	14.10	9.17	7.97	8.90	TWC eff
		C effectivenes		88.1%						61.5%				99.99					99.9%	99.9%	97.8%			99.9%	99.8%	99.2%	99.9%												TWC eff
			- (,	57	52	564	14		5.38E+11	426	391	3300	84 3.75E+12			193		4.10E+10	0	0	225		1.75E+10	1	1	50		7.62E+10	147.4	216.3	144.0	126.0	142.1	9.13	13.70	8.88	7.77	8.75	Bags
				60	55	566	13			445	408	3299	81 -	2	1	195	5		1	1	227	3	-	1	1	52	3		148.1	217.0	144.5	126.4	143.2	9.17	13.75	8.91	7.79	8.82	Modal Dil
	Mean	alues		625	597	7795	2300		-	1452	1377	17048	1255 -	666	638	9336	1612		500	479	6589	2009	-	402	384	4498	3339		135.6	198.8	128.6	113.9	135.0	9.21	14.14	8.93	7.73	8.81	Modal PRE c
				74	68	632	14		-	553	507	3729	91 -	1	1	214	4	· ·	0	1	238	2	-	1	1	57	3	-	151.1	221.5	147.3	128.9	146.2	9.37	14.09	9.08	7.95	9.00	Modal TP
				3.9	3.7	90.7	0.2	0.03	1.84E+10	29.1	27.5		1.4 1.92E+11	0.1	0.0	60.9		4.46E+09	0.1	0.1	151.0		5.48E+09	0.1	0.1	14.4	0.2 2	2.57E+10	0.39	1.34	1.23	0.86	0.65	0.02	0.07	0.08	0.04	0.04	Bags
	Standard	deviation		4.1	3.9	91.5	0.2		-	30.9	29.5		2.2 -	0.2	0.2	60.8	1.2	-	0.2	0.2	151.4	0.2	-	0.1	0.0	14.6	0.3	-	0.46	1.28	1.45	0.99	0.56	0.02	0.06	0.09	0.05	0.04	Modal Dil
				19.5	19.2	233.7	34.6			69.9	68.0	570.8	60.8 -	15.2	16.0	351.1	39.3	•	22.4	22.2	309.0	82.6	-	4.4	4.1		20.5	-	0.84	1.89	1.66	1.68	0.65	0.03	0.07	0.10	0.07	0.05	Modal PRE c
				2.4	2.2	97.2	0.2	-	-	17.3	16.1	289.1	1.6 -	0.2	0.1	72.8	1.0	0.000.00	0.0	0.1	169.7	0.1	-	0.1	0.1	16.1	0.4	-	0.46	1.28	1.46	1.00	0.59	0.02	0.06	0.09	0.04	0.04	Modal TP
				2.3	2.1	52.4 52.8	0.1	0.02	1.06E+10	16.8 17.8	15.9		0.8 1.11E+11 1.3 -	0.1	0.0	35.1	0.7	2.57E+09	0.0	0.0	87.2 87.4	0.1	3.16E+09	0.0	0.0	8.3	0.1	1.48E+10	0.22	0.77	0.71	0.50	0.38	0.01	0.04	0.04	0.02	0.02	Bags Modal Dil
	Type A un	certainty		2.3	2.2	52.8	20.0			40.3	39.2		35.1 -	8.8	9.3	202.7	22.7		0.1 12.9	0.1	87.4	47.7	-	2.5	2.3		0.2		0.27	1.09	0.84	0.57	0.33	0.01	0.03	0.05	0.03	0.02	Modal Dil Modal PRE ci
				1.4	1.3	56.1	0.1			10.0	9.3	166.9	0.9 -	0.0	0.1	42.0	0.6	-	0.0	0.0	98.0	0.1		0.1	0.1		0.2		0.49	0.74	0.90	0.57	0.38	0.02	0.04	0.05	0.04	0.03	Modal TP
Mean	TWC effecti	veness (pre-b	ag)	90.9%				6 -		70.7%				99.99					99.9%		96.7%			99.8%	99.8%	98.9%	99.9%	-											
		veness (pre-b		91.3%					-	71.7%				99.99			99.8%		99.9%		98.3%	99.9%	-	99.9%	99.8%	99.3%	99.9%	-											
Min. 1	WC effection	eness (pre-b	ag)	90.4%	90.8%	91.5%	99.4%	6 -	-	70.1%	71.1%	79.4%	92.8% -	99.89	6 99.99	6 97.4%	99.6%	-	99.9%	99.9%	93.8%	99.9%	-	99.8%	99.8%	98.5%	99.9%	-											
Mean	WC effecti	veness (pre-p	ost)	88.2%	88.6%	91.9%	99.4%	6 -	-	61.9%	63.1%	78.2%	92.8% -	99.89	6 99.99	6 97.7%	99.7%	1.1	99.9%	99.9%	96.5%	99.9%	-	99.8%	99.8%	98.7%	99.9%	-											
Max. T		eness (pre-p		88.3% 88.1%						62.9% 61.4%				99.99		6 98.7% 6 97.2%	99.8% 99.7%		99.9%		98.4% 93.2%	99.9%	-	99.9% 99.8%	99.8%	99.2% 98.4%	99.9% 99.9%	-											



Table 17 Emissions and fuel consumption results from the Fiat Tipo 1.4 vehicle over the WLTC cycle for TWC High S at 100 cycles

	utomotive Re-	SMA search and Deve issions Testing Li	elopment	t Institute Ltd																WLT	P test (Reg 20	17/115	1) - WL	LTC dr	iving c	cycle														
/IN: ZFA356	00006K2025	52			Vehi	cle mo	del:					Fiat 1	Tipo 1.4 L	PG							Er	nission st	andard:	Euro 6								Tyr	es:			Contine	antal ContiEcoCo	intact 5 225/45	i5 R17 V XL		
nertia [kg]:		1509				Er	ission WLT	C				Er	nission LOV	V			Emi	ssion MIDE	DLE			Er	nission HIG	н			Em	ission Ex-H	GH			C	O2 emissio	n			Fi	uel consump			_
/lieage(km)	Date	Chassis dyno F0/F1/F2	Test	40. TU 10	NMHC		[mg/km]		PM	PN	THC	NMHC	[mg/km] CO	NOx	PN	THC	NMHC	[mg/km] CO	NOx	PN	THC	NMHC	[mg/km] CO		PN	THC	NMHC	[mg/km] CO	NOx	PN	WLTC	LOW	[g/km] MIDDLE	HIGH	Ex-HIGH	WLTC	LOW	[I/100 km] (2) MIDDLE		Ex-HIGH	Note 1
		FUF UF2		THC	DAL DIL - P			x	РМ	PN	THC	NINHC	00	NUX	PN	THC	NMHC	CO	NUX	PN	THC	NMHC	00	NOx	PN	THC	NMHC	00	NUX	PN	WLIC	LOW	MDDLE	HIGH	EX-HIGH	WEIG	LOW	MIDDLE	HIGH	EX-HIGH	
geing stage:	100 cycles	45.1	1	BAG - MC 54	50 SO	47			0.41	4.17E+11	401	371	3176	110	3.00E+12	1	1	112	41	1.62E+10	1	1	68	8	9.76E+09	1	1	19	4	3.71E+10	146.6	216.5	142.3	125.0	141.6	9.07	13.69	8.76	7.69	8.71	Bags
		45.1	1		52	47			0.41	4.1/6+11	401	3/1 383	31/6	110	3.00E+12	2	1	112	41	1.02E+10	1	1	69	8	9.702+09	1	1	19	4	3.71E+10	140.0	216.5	142.5	125.0	141.6	9.07	13.09	8.76	7.09	8.71	Modal Dil
5 514	24.06.2019	0.0390	L1-03	38 581	555	72					1366	1300	16547	1222		616	591	8520	1604		450	431	5633	2022		381	364	4353	3296		135.3	199.8	127.1	114.1	134.4	9.13	14.14	8.75	7.64	8.76	Modal PRE cat
		0.0350		68	63	50					509	471	3385	123		1	1	113	40		0	1	74	6		1	1	23	3		150.0	221.6	145.3	127.7	145.5	9.29	14.05	8.95	7.86	8.95	Modal TP
	TM	VC effectivenes	ss (pre-b					8.8%			70.6%				<u>د</u> -	99.8%	99.8%				99.9%	99.9%	98.8%			99.7%	99.7%		99,9%									1 0.00			TWC eff
		/C effectivenes:						8.8%			62.7%					99.8%					99.9%					99.8%															TWC eff
		45.1	1 1	66	61	52			0.62	5.63E+11	490	454	3441	101	4.02E+12	2	1	165	4	3.24E+10	1	1	81		8.53E+09	1	1	17		4.93E+10	146.6	216.0	142.2	124.4	142.2	9.08	13.71	8.76	7.66	8.75	Bags
5 537	25.06.2019	-0.87	L1-03	69	64	52	1 19	,			511	475	3430	100	-	2	1	167	4		1	1	83	3	-	1	1	18	10	-	147.3	216.4	142.8	124.7	143.4	9.12	13.74	8.80	7.68	8.82	Modal Dil
5 537	25.06.2019	0.0390	L1-03	628	600	73	9 234	12	-	1.1	1523	1449	16936	1275	-	690	664	8989	1616		479	459	5824	2068	1.1	384	366	4260	3400		135.2	197.9	126.7	113.2	135.5	9.15	14.09	8.79	7.61	8.82	Modal PRE cat
				86	80	58	21			100 A	637	591	3836	113	-	1	1	181	4	1.1	0	1	81	2	1.1	1	1	23	14	1.1	150.4	221.2	145.7	127.2	146.4	9.32	14.09	8.98	7.83	9.01	Modal TP
		VC effectivenes			% 89.8	6 9	.9% 99	9.2%		1.1.1	67.8%	68.6%			6 -	99.7%	99.8%	98.2%	99.7%	1.1	99.8%	99.9%	98.6%			99.7%	99.7%	99.6%	99.7%												TWC eff
	TW	C effectivenes	s (pre-p					9.1%		1.1	58.2%					99.8%	99.8%	98.0%			99.9%	99.9%	98.6%			99.8%	99.7%		99.6%												TWC eff
		45.1		55	50	46			0.61	5.14E+11	407	374	3140	102	3.72E+12	1	1	107	23	2.52E+10	0	0	58	5	1.43E+10	1	1	17	4	1.97E+10	145.9	215.3	141.9	124.4	140.6	9.03	13.62	8.74	7.66	8.65	Bags
5 560	26.06.2019	-0.87	L1-03	45 58	53	46			-	•	425	390	3120	92	-	2	1	109	21		1	1	61	4	-	1	1	17	4	-	146.5	216.0	142.0	124.8	141.8	9.07	13.67	8.74	7.68	8.72	Modal Dil
		0.0390		587	560	71:					1406	1332	16382	1249	-	608	583	8325	1627	-	462	444	5604	2002	1.1	375	358	4303	3280	-	134.5	198.4	126.9	112.8	133.6	9.07	14.05	8.72	7.57	8.70	Modal PRE cat
				69	63	51			-	1.1	510	469	3508	107	-	1	1	105	22		0	1	59	4			1	22	3		149.5	220.6	144.8	127.3	144.7	9.26	14.00	8.91	7.84	8.90	Modal TP
		VC effectivenes /C effectivenes						9.1%	-		71.1%					99.8%		98.7%	98.6%		99.9%	99.9%	99.0%			99.8%			99.9%												TWC eff
	100	C effectivenes	is (pre-p	ost) 88.3	% 88.7	× 9 48			0.55	4.98E+11	63.7% 433	64.8%	78.6%	91.49	3.58E+12	99.8%	99.8%	98.7%	98.6%	2.46E+10	99.9%	99.9%	98.9% 69	99.8% 5	1.09E+10	99.8%	99.7%	99.5%	99.9%	3.54E+10	146.3	215.9	142.1	124.6	141.4	9.06	13.67	8.75	7.67	8.70	Bags
				61	56	40			-	4.00E+11	450	400	3232	104	3.000 + 12	2	1	130	23	2.402+10	1	1	71	5	1.052710	1	1	18	6	3.04E+10	140.3	216.5	142.4	124.0	141.4	9.10	13.07	8.77	7.69	8.77	Modal Dil
	Mean	values		599	572	72					1432	1360	16622	1249		638	613	8611	1616		464	445	5687	2030		380	363	4305	3325		135.0	198.7	126.9	113.4	134.5	9.11	14.09		7.61	8.76	Modal PRE cat
				74	69	53					552	510	3577	114		1	1	133	22		0	1	71	4		1	1	23	7		150.0	221.1	145.3	127.4	145.5	9.29	14.05	8.95	7.84	8.95	Modal TP
				5.6	5.3	26			0.10	6.07E+10	40.8	38.7	134.3	3.9	4.28E+11	0.3	0.2	26.4	14.8	6.61E+09	0.2	0.1	9.4	2.1	2.50E+09	0.2	0.1	0.9	3.3	1.21E+10	0.33	0.47	0.17	0.30	0.67	0.02	0.04	0.01	0.02	0.04	Bags
				5.9	5.7	26					43.2	41.5	136.2	6.4		0.1	0.1	26.6	14.6		0.0	0.1	9.1	21		0.1	0.1	0.9	3.2		0.33	0.42	0.34	0.24	0.67	0.02	0.03	0.02	0.01	0.04	Modal Dil
	Standard	deviation		20.7	20.1		3 29.0				66.6	64.1	231.9	21.5		36.9	36.3	278.6	9.2		11.8	11.4	97.7	27.6		3.9	3.6	38.2	53.0		0.37	0.81	0.14	0.52	0.79	0.03	0.04	0.03	0.03	0.05	Modal PRE cat
				8.1	7.7	34.			-		60.0	57.0	190.3	6.7		0.1	0.0	34.1	14.8		0.0	0.0	9.3	1.5		0.1	0.0	0.3	4.9		0.36	0.41	0.38	0.22	0.72	0.03	0.04	0.03	0.01	0.04	Modal TP
				3.3	3.1	15	3 1.8	3	0.06	3.50E+10	23.6	22.4	77.5	2.3	2.47E+11	0.2	0.1	15.2	8.6	3.82E+09	0.1	0.1	5.4	1.2	1.44E+09	0.1	0.1	0.5	1.9	7.01E+09	0.19	0.27	0.10	0.17	0.38	0.01	0.02	0.01	0.01	0.02	Bags
	Tune A			3.4	3.3	15	5 1.9	2	-		24.9	24.0	78.7	3.7	-	0.0	0.0	15.3	8.4		0.0	0.1	5.2	1.2		0.0	0.0	0.5	1.8		0.19	0.24	0.20	0.14	0.39	0.01	0.02	0.01	0.01	0.02	Modal Dil
	Type A un	icercainty		11.9	11.6	63	1 16.	8	-		38.4	37.0	133.9	12.4	-	21.3	21.0	160.9	5.3		6.8	6.6	56.4	16.0		2.2	2.1	22.0	30.6		0.21	0.47	0.08	0.30	0.45	0.02	0.02	0.02	0.02	0.03	Modal PRE cat
				4.7	4.5	20.	2 1.7	7	-		34.6	32.9	109.9	3.9	-	0.0	0.0	19.7	8.6		0.0	0.0	5.4	0.9		0.1	0.0	0.1	2.8	-	0.21	0.23	0.22	0.12	0.41	0.01	0.02	0.02	0.01	0.03	Modal TP
		iveness (pre-b		90.3				9.0%			69.8%	70.7%				99.8%					99.9%	99.9%	98.8%		1	99.8%		99.6%													
		iveness (pre-b	bag)	90.7	% 91.0			9.2%			71.1%	71.9%				99.8%					99.9%	99.9%	99.0%		1.1	99.8%		99.6%													
Min.	TWC effectiv	iveness (pre-b		89.4				8.8%			67.8%	68.6%				99.7%					99.8%	99.9%	98.6%			99.7%		99.6%													
Min. Mean	TWC effection TWC effection	iveness (pre-p	post)	87.6	% 88.0	% 9	.6% 99	9.0%	1		61.5%	62.6%	78.5%	90.89	6 -	99.8%	99.8%	98.5%	98.6%	1.1	99.9%	99.9%	98.7%	99.8%	1.1	99.8%	99.7%	99.5%	99.8%	1.1											
Min. Mean Max.	TWC effection TWC effection TWC effection		oost) oost)		% 88.0 % 88.7	%9 %9	1.6% 99		-			62.6% 64.8%	78.5% 79.5%	90.89 91.49	6 -		99.8% 99.8%	98.5% 98.7%	98.6% 99.8%			99.9% 99.9%	98.7% 98.9%	99.8% 99.9%			99.7% 99.7%	99.5% 99.5%	99.8% 99.9%												



Table 18 Emissions and fuel consumption results from the Fiat Tipo 1.4 vehicle over the WLTC cycle for TWC High S at 175 cycles

	Automotive Re	SMA esearch and Dev issions Testing L	elopment	t Institute Ltd																WLTF	P test (Reg 20	17/115	51) - WI	LTC dr	iving c	cycle														
VIN: ZFA35	500006K202	52			Veh	icle mo	del:					Fia	t Tipo 1.4	LPG							Er	nission s	tandard:	Euro 6								Ty	res:			Conti	ental ContiEco	Contact 5 225/	45 R 17 V XL		
Inertia [kg]:		1509				En	ission WLT	TC					Emission LO	w				ion MIDD	LE			Er	nission HIG	н			En	ission Ex-HIG	H			0	CO ₂ emissio	on				Fuel consum			_
Mileage[km]	Date	Chassis dyno F0/F1/F2	Test N	No. THC	NMHC	0	[mg/km])v	PM	PN	THC	NMHG	[mg/km]	NOx Pt	и тн	r T	NMHC	[mg/km] CO	NOx	PN	THC	NMHC	[mg/km] CO	NOx	PN	THC	NMHC	[mg/km] CO	NOx	PN	WLTC	LOW	MDDLE	HIGH	Ex-HIGH	WLTC	LOW	· · · · · · · · · · · · · · · · · · ·		Ex-HIGH	Note 1
Ageing stage	: 175 cycles				DDAL DIL - P			~			mo	1 100	00	1 100		~	Tunito	00	HOX		116	144110	00	NOX		110	144410	00	140.4		METO	LOII	MADDLL	TINGIT	Exhibit	mere	1.011	MIDDLL	11011		·
and sugar		45.1	1	55	49	64		7	0.60	5.05E+11	412	369	4260	112 3.61E	+12 1		1	206	4	3.43E+10	0	0	104	3	1.99E+10	0	0	25	3	4.23E+10	145.4	215.5	142.2	123.9	140.0	9.02	13.74	8.77	7.63	8.61	Bags
5 654	07.08.2019	-0.87	L1-03	57	51	64					429	385		105 -			1	209	4	-	1	0	106	3	-	1	0	26	3		146.4	216.4	142.9	124.6	141.4	9.08	13.81		7.67	8.70	Modal Dil
0.004	07.08.2019	0.0390	L1-03	578	550	765			1.0		1336	1254		1211 -	60	9	582	9149	1610	1.0	462	443	6054	2005		380	363	4484	3226	1.1	134.5	199.5	128.3	112.9	132.8	9.12	14.25		7.62	8.67	Modal PRE cat
				74	67	73					555	501		124 -	1		1	216	3		0	1	100	3		1	1	28	3		149.4	221.2	145.7	127.1	144.3	9.27	14.18	8.98	7.83	8.88	Modal TP
		WC effectivene						9.2%		-	69.2%					9.8%	99.9%	97.7%	99.8%	1.1	100.0%		98.3%			99.9%			99.9%												TWC eff
	ти	VC effectivenes	s (pre-p		51 ST			9.2%		-	58.5%					9.8%	99.8%	97.6%	99.8%		99.9%	99.9%	98.3%			99.8%	99.8%	99.4% 34	99.9%												TWC eff
		45.1 -0.87		56	53	53		_	0.31	4.42E+11	415 434	380		91 3.17E	+12 2		1	212	3	2.34E+10	0	0	124	2	1.35E+10	1	1	34	3	3.93E+10	146.5 147.3	219.6 220.4	143.4 143.8	124.4	140.3	9.07	13.90		7.66	8.63	Bags Modal Dil
5 677	08.08.2019	0.0390	L1-03	98 592	565	756					434	1398		1289 -	61		590	213 9543	1581		475	455	6047	2 1997		382	365	34 4377	3236		134.7	220.4	143.8	125.0		9.12	13.96		7.62	8.71	Modal Dil Modal PRE cat
		0.0350		69	63	59					516	474		101 -	2		1	226	3		0	1	129	2		1	1	37	3		150.3	225.1	146.5	127.4		9.31	14.30		7.85	8.89	Modal TP
	71	WC effectivene	ss (pre-b					9.4%		-	70.2%					9.8%	99.9%	97.8%	99.8%		99.9%		97.9%			99.8%	99.9%		99.9%												TWC eff
		VC effectivenes						9.3%		-	62.9%					9.7%	99.8%	97.6%	99.8%		99.9%					99.8%			99.9%												TWC eff
		45.1	1	47	42	51	2 15	5	0.45	4.33E+11	351	316	3429	100 3.11E	+12 1		1	142	2	2.78E+10	0	0	81	2	4.51E+09	1	0	13	2	4.07E+10	145.2	217.2	141.9	123.3	139.3	8.99	13.75	8.74	7.59	8.57	Bags
5 701	09.08.2019	-0.87	L1-04	49	44	51	15	5			365	329	3430	97 -	2		1	144	2		1	0	83	2		1	1	13	3		146.0	218.0	142.3	123.8	140.6	9.04	13.80	8.77	7.62	8.65	Modal Dil
5701	09.08.2019	0.0390	L1-04	564	536	730				-	1311	1238		1285 -	60	4	577	8782	1590	1.0	437	418	5827	2001		372	354	4353	3172		134.8	200.8	127.8	113.4		9.10			7.62		Modal PRE cat
				61		56				-	458	414		113 -	1		1	153	2		0	1	82			1	1	17	3		148.9	222.5	145.0	126.2	143.4	9.22	14.13	8.93	7.77	8.82	
		WC effectivene						9.3%	-	-	73.2%					9.8%	99.9%	98.4%				100.0%				99.8%			99.9%												TWC eff
	ти	VC effectivenes	s (pre-p					9.2%	-	-	65.1%					9.8%	99.8%	98.3%	99.9%	-	99.9%		98.6%			99.7%			99.9%												TWC eff
				52		56			0.45	4.60E+11	393 409	355		101 3.30E			1	187 189	3	2.85E+10	0	0	103		1.26E+10	1	0	24	3	4.08E+10	145.7 146.6	217.4	142.5 143.0	123.9	139.9	9.03	13.80	8.78	7.63	8.61	Bags Modal Dil
	Mean	values		578	49	752			-		409	1270		1261 -	2	0	1 583	9158	3 1594		1 458	438	5976	3 2001		378	0 361	24 4404	3211		146.6	218.3	143.0	124.5		9.08	13.86		7.62	8.65	Modal DR Modal PRE cat
				68	62	63				-	510	463		113 -	2		1	198	2		430	430	104	2007		3/0	307	27	3211		149.5	201.2	145.7	126.9	144.0	9.12	14.20		7.81	8.86	Modal TP
				3.9	37	58			0.12	3.18E+10	29.5	28.1		8.5 2.25E			0.1	31.7	0.7		0.1	0.1	17.5		6.30E+09	0.1	0.1	8.5	0.2	1.20E+09	0.58	1.68	0.65	0.44	0.41	0.04	0.07	0.04	0.03	0.03	Bags
				4.2		60.			0.12	0.102.10	31.4	30.0		6.5 -	0.3			31.5	0.7		0.1	0.1	17.6	0.4	0.002.00	0.1	0.1	8.6	0.2	1.202.100	0.57	1.64	0.61	0.47	0.45	0.04	0.07		0.03	0.03	Modal Dil
	Standard	deviation		11.6							33.2	34.9		35.7 -	5.0			310.4	12.2		15.5	15.6	105.5	3.5		4.4	4.5	56.9	28.3		0.10	1.61	0.37	0.21	0.24	0.01	0.08	0.03	0.00	0.02	Modal PRE cat
				5.2	4.7	74.	\$ 1.3	3		-	40.0	36.2	552.0	9.6 -	0.	1	0.1	32.3	0.5		0.0	0.0	19.2	0.3		0.1	0.0	8.5	0.2		0.59	1.61	0.63	0.50	0.47	0.04	0.07	0.04	0.03	0.03	Modal TP
				2.2	2.1	33.	7 0.1	7	0.07	1.83E+10	17.0	16.2	244.4	4.9 1.30E	+11 0.1	1	0.1	18.3	0.4	2.59E+09	0.1	0.0	10.1	0.2	3.64E+09	0.1	0.1	4.9	0.1	6.95E+08	0.34	0.97	0.38	0.26	0.23	0.02	0.04	0.02	0.02	0.01	Bags
	Type A u	ocertainty		2.4	2.3	34.					18.2	17.3		3.8 -			0.1	18.2	0.4	-	0.1	0.0	10.2	0.2	-	0.1	0.1	5.0	0.1	-	0.33	0.95	0.35	0.27	0.26	0.02	0.04	0.02	0.02	0.02	Modal Dil
	· ,pe A u	recruitly		6.7	6.7	93.				-	19.1	20.1		20.6 -	3.3		3.0	179.2	7.1	-	8.9	9.0	60.9	2.0	-	2.6	2.6	32.9	16.4	-	0.06	0.93	0.21	0.12	0.14	0.01	0.05	0.02	0.00	0.01	Modal PRE cat
				3.0	2.7	43.			-	-	23.1	20.9		5.5 -	0.:		0.0	18.6	0.3	-	0.0	0.0	11.1	0.2	-	0.0	0.0	4.9	0.1		0.34	0.93	0.36	0.29	0.27	0.02	0.04	0.02	0.02	0.02	Modal TP
		tiveness (pre-l		90.9				9.3%			70.8%					9.8%	99.9%	98.0%	99.8%		99.9%		98.3%			99.8%			99.9%												
		iveness (pre-b		91.				9.4%			73.2%					9.8%	99.9%	98.4%	99.9%		100.0%		98.6%			99.9%			99.9%												
		iveness (pre-b iveness (pre-p		90.				9.2%	1.0		69.2%					9.8% 9.8%	99.9% 99.8%	97.7% 97.8%	99.8% 99.8%		99.9%		97.9% 98.3%			99.8% 99.8%			99.9% 99.9%												
		iveness (pre-p iveness (pre-p		88.				9.2%	· ·		62.1%					9.8%	99.8%	97.8%	99.8%		99.9%		98.3%			99.8%			99.9%												
		veness (pre-p		89.				9.3%					1% 72.5				99.8%				99.9%		98.6%			99.8%		99.6%													
Min.	I WYC effecti	veness (pre-p	osuj	87.4	87.5	- jeve	.3/6 9	3.4/0			58.57	60.	1/0] /2.5	07./76	9	2.7/0	22.8%	57.6%	55.8%		59.9%	59.9%	57.9%	39.9%		39.7%	39.8%	59.1%	55.9%												



Table 19 Emissions and fuel consumption results from the Fiat Tipo 1.4 vehicle over the WLTC cycle for TWC High S at 250 cycles

BOSMAL A	atomotive Res	SAMA search and Deve ssions Testing Li	alopment Instit	tute Ltd																	,	WLTP	test (R	Reg 20	7/115	1) - WI	.TC dr	iving o	cycle														
VIN: ZFA3560	0006K2025	2			Vehic	le mod	əl:					Fia	t Tipo '	.4 LPG									Em	ission st	andard:	Euro 6								Tyr	es:			Contir	ental ContiEcr	oContact 5 225	5/45 R 17 V XL		
Inertia [kg]:		1509					ision WLTC						Emission					E	mission N					En	ission HIG	н			En	hission Ex-H	IGH			C	CO ₂ emissio	n				Fuel consur			
Mieage(km)	Date	Chassis dyno	Test No.			· · · · · · · · · · · · · · · · · · ·	[mg/km]						[mg/l						[mg/kr	-					[mg/km]				·	[mg/km]	·				[g/km]					[l/100 km]	·		Note 1
01.7		F0/F1/F2		THC	NMHC	co	NOx	PI	м	PN	THC	NMHC	; c	>	XOX	PN	THC	NMHC	co	N	2×	PN	THC	NMHC	co	NOx	PN	THC	NMHC	co	NOx	PN	WLTC	LOW	MIDDLE	HIGH	Ex-HIGH	WLTC	LOW	MIDDLE	E HIGH	Ex-HIGH	н
Ageing stage: 2					AL DIL - PRI																																						
		45.1		65	60	461			74 4	4.77E+11	479	445				3.43E+12	2		114		5 2	.43E+10	1	1	39		6.68E+09	1		31		4.07E+10	146.2			124.6		9.05					
5 749	19.12.2019	-0.87	L1-0709	<u>68</u> 554	63 528	466 6444				-	504	470			112	-	2 559	534	7347				1 432	1 412	41 5465	4 2426		2 354	1 336	32 4542	3439		147.5	214.4 199.4	142.1	125.5 123.0		9.13 9.45					
		0.0390		71	528	446				-	526	488			129		2		123			-	432	412	46	2420		304	330	4542	3439		141.9					9.45		9.07		9.19	
	TW	/C effectivenes	s (pre-bag)	88.3%							64.8%				92.7%		99.7%				9.8%		99.8%	99.8%	99.3%			99.6%	99.7%		99.9	1%	102.0	110.0	141.0	104.7	140.0				0.10		TWC eff
		C effectivenes		87.2%						-	61.4%				92.1%		99.7%				9.7%		99.9%	99.8%	99.2%			99.6%															TWC eff
		45.1		70	65	613	16	0.6	69 5	5.03E+11	520	480	38	38	98	3.61E+12	2	1	238		4 3	89E+10	1	1	121	3	5.75E+09	1	1	40	3	4.11E+10	146.2	212.7	142.0	124.9	142.3	9.06	13.55	8.76	7.69	8.76	Bags
5 772	20.12.2019	-0.87	L1-0712	74	68	617	16			-	547	507	38	21	96	-	2	1	238		1	-	1	1	122	4		1	1	40	3	-	147.4	213.8	142.8	125.9	143.8	9.14	13.63	8.81	7.76	8.85	Modal Dil
5772	20.12.2019	0.0390	L1-0/12	543	516	6862					1347	1285			578		545	517	8482		19	1.00	424	405	5672	2373		344	326	4599	3478		140.8	197.4	133.1	122.4		9.42					
				77	71	606					575	531			110	1.0	1		249				0	1	129	3	1.1	1	1	44	3		151.2	210.7	146.8	132.1	148.0	9.37	13.43	9.05	8.14	9.11	
		VC effectivenes		87.1%						-	61.4%				93.8%	-	99.7%				9.8%	-	99.8%		97.9%			99.6%															TWC eff
	TW	C effectivenes	s (pre-post)	85.8%	86.2%	91. 778				- 5.07E+11	57.3% 478	434			93.0% 107	3.62E+12	99.7%	99.8	320		9.8%	.36E+10	99.9%	99.9%	97.7%		6.39E+09	99.6%	99.7%	99.0%	99.9		147.4	214.0	142.3	127.1	143.0	9.15	13.72	8.78	7.83	8.80	TWC eff Bags
		-0.87		69	62	784				5.0/E+11	478	434	48		107	3.62E+12	2	1	320			30E+10	1	1	1/8	3	6.39E+09	2	1	48	4	5.09E+10	147.4	214.0	142.3	127.5		9.15					
5 795	30.12.2019	0.0390	L1-0716	571	541	7595				-	1291	1213			112		571		8536		96		458	437	6292	1997		399	381	4597	3253		135.8	198.3	130.1	114.3		9.19					
		0.0000		79	71	916					586	526	56		93		2	1	408				0	1	186	2		1	1	54	3		151.6	220.5	146.1	130.0	147.5	9.43				9.08	
	τw	C effectivenes	s (pre-bag)	88.7%	89.2%	89.	3% 99.2	2% -			62.9%	64.	2% 7	1.9%	90.4%		99.7%	99.8	% 96	.3% 9	9.9%		99.9%	99.9%	97.2%	99.8%		99.7%	99.8%	99.0%	99.9	1% -											TWC eff
	TWO	C effectivenes	s (pre-post)	86.1%	86.9%	87.	9% 99.4	4% -		-	54.6%	56.	5% (6.9%	91.6%		99.6%	99.8	% 95	.2% 9	9.9%		99.9%	99.9%	97.0%	99.9%		99.6%	99.7%	98.8%	99.9	1% -	1										TWC eff
				66	61	618	17	0.8	81 4	4.96E+11	492	453	39	35	108	3.55E+12	2	1	224		3 2	.89E+10	1	1	113	4	6.27E+09	1	1	40	3	4.42E+10	146.6	213.1	141.8	125.5	142.8	9.09	13.58				
	Mean	values		70	65	622	17			-	519	480	39		105	-	2	1	224				1	1	115	4		2	1	40	3		147.8	214.6	142.7	126.3	144.4	9.17	13.68			8.89	
				556	529	6967			·	-	1334	1267	143		437	-	558	530	8121		51	-	438	418	5810	2266	-	366	348	4579	3390	-	139.5	198.4	132.5	119.9	138.5	9.36				9.03	
				76	69	656		-		-	562	515	41		111	-	2	1	260			-	0	1	120	3	-	1	1	45	3	-	151.7	214.8	146.8	131.6	148.3	9.41	13.72			9.12	
			-	2.5	2.6	129.3		0.1		1.32E+10	19.4 19.7	19.7			8.5	8.47E+10	0.1	0.1	84.5		.4 7 3	.07E+09	0.1	0.0	57.0 57.2	0.4	3.89E+08	0.0	0.0	6.7	0.2	4.72E+09	0.56	0.63	0.47	1.11 0.84	0.33	0.05	0.10			0.02	
	Standard of	deviation	ŀ	11.6	2.5	475.5				-	30.5	38.8	207		30.3		10.5	9.5	548.				14.4	13.8	351.4	0.4 190.8		23.9	24.0	26.3	98.0	+ :	2.64	0.78	1.76	3.94	3.00	0.04				0.03	
			ŀ	3.5	2.5	195.2					26.0	19.1			14.6		0.3	0.1	116.				0.1	0.0	57.5	0.7		0.1	0.1	7.2	0.0		0.47	4.14	0.54	1.14	0.77	0.03	0.36			0.05	
				1.5	1.5	74.6	0.8	0.0	08 7	7.59E+09	11.2	11.4				4.89E+10	0.1	0.1	48.8		.8 4	08E+09	0.0	0.0	32.9	0.2	2.25E+08	0.0	0.0	3.9	0.1	2.72E+09	0.32	0.36	0.27	0.64	0.19	0.03				0.01	
	Type A un	costo inte	ľ	1.4	1.5	74.8	0.6	-		-	11.4	11.4	40	2.0	3.7	-	0.1	0.0	48.4	0	8	-	0.0	0.0	33.0	0.2		0.1	0.0	3.9	0.1	-	0.30	0.45	0.28	0.48	0.26	0.02	0.06	0.02	0.03	0.02	Modal Dil
	rype A un	certainty		6.7	5.9	274.6	100.9			-	17.6	22.4			32.9	-	6.1	5.5	316.4		4.8	-	8.3	8.0	202.9	110.2		13.8	13.8	15.2	56.6	-	1.52	0.48	1.02	2.28	1.73	0.07	0.11			0.10	
				2.0	1.5	112.7				-	15.0	11.0			8.4		0.2	0.1	67.4				0.0	0.0	33.2	0.4		0.0	0.0	4.1	0.0		0.27	2.39	0.31	0.66	0.44	0.01	0.21	0.01	0.04	0.03	Modal TP
		iveness (pre-b		88.0%							63.1%				92.3%		99.7%				9.8%		99.8%	99.8%	98.1%			99.6%															
		veness (pre-b		88.7%						-	64.8%				93.8%		99.7%				9.9%	-	99.9%	99.9%	99.3%			99.7%															
		veness (pre-b		87.1%						-	61.4%				90.4%		99.7%				9.8%	-	99.8%	99.8%	97.2%			99.6%															
iviean i		veness (pre-p		86.4%							57.8%				92.2% 93.0%		99.7% 99.7%				9.8%	-	99.9%	99.9%	98.0%			99.6%															
May T																																											
	WC effectiv	veness (pre-pr veness (pre-pr		87.2%	87.6%						61.4%				93.0%		99.6%				9.7%		99.9% 99.9%	99.9% 99.8%	99.2% 97.0%			99.6% 99.6%															



Table 20 Emissions and fuel consumption results from the Fiat Tipo 1.4 vehicle over the constant speed cycle for TWC High S

		tesearch and I	Development Institution ng Laboratory	tute Ltd					I	-		om tes stabilis	-			-	•			
VIN: ZFA35	600006K202	52			Vehicle	model:					Fiat	Tipo 1.4	LPG	Ту	res:	Continenta	al ContiEco	Contact 5 2	225/45 R17	7 V XL
Inertia [kg]:		1509		P	hase 1 - 8	0 km/h in 5	th gear (ho	t stabilised)		Phase 2 - 8	30 km/h in 5	th gear (hot	stabilised	0	CO ₂ e	mission	Fuel cor	sumption	1
Mileage	1	Chassis	Γ			[mg/	·····		/			[mg/					km]		km] ⁽²⁾	 Note 1
[km]	Date	dyno F0/F1/F2	Test No.	THC	NMHC	co	NOx	PM	PN	THC	NMHC	co	NOx	PM	PN	P1	P2	P1	P2	-
Ageing stag	e: 0 cycles	•		BAG - MOD	AL DIL - PR	E - POST														
		45.1		0	0	26	0	0	1.81E+08	0	0	25	0	0.01	1.90E+08	103.7	100.5	6.29	6.24	Bags
4 523	08.11.2018	-0.87	L1-0496	0	0	26	0	-	-	0	0	24	0	-	-	103.9	100.6	6.30	6.25	Modal Dil
4 525	06.11.2016	0.0390	L1-0496	305	291	2984	2221	-	-	300	286	2970	2219	-	-	100.3	97.1	6.43	6.38	Modal PRE cat
				0	0	34	0	-	-	0	0	32	0	-	-	105.9	102.6	6.42	6.37	Modal TP
	1	WC effective	eness <u>per phase</u>	100.00%	99.96%	98.87%	99.99%	-	-	100.00%	99.96%	98.92%	99.99%	-	-					
			of <u>both phases</u>)		99.96%	98.90%	99.99%	-	-	-	-	-	-	-	-					
Max.	TWC effectiv	eness (max.	of <u>both phases</u>)	100.00%	99.96%	98.92%	99.99%	-	-	-	-	-	-	-	-					
Min.	TWC effectiv	eness (min.	of <u>both phases</u>)	,	99.96%	98.87%	99.99%	-	-	-	-	-	-	-	-					
Ageing stage	e: 250 cycles	r		BAG - MOD															,	_
		45.1		0	0	46	0	0.09	1.67E+09	0	0	38	0	0.17	1.84E+09	104.4	102.9	6.43	6.33	Bags
5 899	07.01.2020	-0.87	L1-0005	1	0	46	0	-	-	1	0	38	0	-		104.7	103.1	6.44	6.34	Modal Dil
		0.0390		282	268	3152	2218	-	-	272	258	3024	2159	-	-	101.1	99.7	6.58	6.47	Modal PRE cat
		<u> </u>	L	0	0	51	0	-	-	0	0	42	0	-	-	106.8	105.1	6.57	6.47	Modal TP
			eness <u>per phase</u>		99.95%	98.39%	99.99%	-	-	100.00%	99.94%	98.61%	99.99%	-	-					
			of both phases)	(99.94%	98.50%	99.99%	-	-	-	-	-	-	-	-					
			of both phases)		99.95%	98.61%	99.99%	-	-	-	-	-	-	-	-					
Min.	I WC effectiv	reness (min.	of both phases)	100.00%	99.94%	98.39%	99.99%	-		-	-	-	-	-	-					



report no. 7/23

APPENDIX - FUEL CERTIFICATES



Appendix 1:

No Parameter Text standard Unit Result comparison 1 Sulphur content (A) ASTM D 6667-14 mg/kg 8.2		Re	sults of analysis (PP3/2326/20)18)	
1 Sulphur content (A) mg/kg 8.2 2 Density at 15 °C 8973:2000 km/m³ 549.2 - Absolute vapor pressure at temperature 20 °C PN-EN ISO 8973:2000 km/m³ 549.2 - Absolute vapor pressure at temperature 20 °C PN-EN ISO 8973:2000 kPa 514 - Methane PN-EN ISO 8973:2000 kPa 514 - ethene PN-EN ISO 8973:2000 kPa - - ethene - - - - - propane - - - - - - propane -	No	Parameter	Test standard	Unit	Result	Requirements for comparison
2 Density at 15 °C 8973:2000 km/m° 549;2 - Absolute vapor pressure at temperature 20 °C PN-EN ISO PN-EN 589 + A1:2012 app. C kPa 514 - Hydrocarbon composition methane - - - ethene ethene 0.6 - - - propane propane - - - - propane propane - - - - - propane propane - - - - - n-butane propadiene 27941:2015-12 % mol % mol - - isobutene 27941:2015-12 (A) % mol - - - isopentane - - - - - - - 1,3-butadiene - - - - - - - - - - - - - - -	1	Sulphur content	(A)	mg/kg	8.2	
Absolute vapor pressure at temperature 20 °C 8973:2000 PN-EN 589 + A1:2012 app. C kPa 514 - Hydrocarbon composition methane -	2	Density at 15 °C	8973:2000	km/m³	549.2	-
methane	3		8973:2000 PN-EN 589 +	kPa	514	-
4 <		Hydrocarbon composition				-
ethane 0.3 - ethane 0.1 - propane propane propane isobutane		methane			1	-
ethene <		ethane			1	-
4 propane 44.6 . 9ropene . 38.1 . isobutane . . . cyclopropane . . . n-butane . . . propadiene . . . propadiene . . . 1-butene . . . isobutene . . . 2-transbutene . . . isopentane . . . 2-transbutene . . . isopentane . . . 2-cisbutene . . . n-pentane . . . 3-methylbutene-1 . . . 1,2-butadiene <		ethene			1	-
Image: propene Image: solutane Image: solu		propane	1		44.6	-
isobutane 9.9 cyclopropane		propene	1		< 0.1	-
4 cyclopropane - <t< td=""><td></td><td>isobutane</td><td>-</td><td></td><td>9.9</td><td>-</td></t<>		isobutane	-		9.9	-
n-butane PN-EN % mol 44.6 - 1-butene 27941:2015-12 (A) % mol 0.2 - 2-transbutene 2-transbutene (A) % (m/m) 0.2 - 2-transbutene 2-transbutene - <0.1		cyclopropane	-		< 0.1	-
4 propadiene - - - - - - - - - - 0.1 - 0.2 0.2 - 0.1 - 0.2 - 0.1 - - 0.1 - - 0.1 - - 0.1 - - 0.1 - - 0.1 - - 0.1 - - 0.1 -		n-butane	-		44.6	-
4 1-butene PN-EN 27941:2015-12 (A) % mol % mol % (m/m) 0.2 - 2-transbutene (A) % mol % (m/m) 0.1 - 2-transbutene <0.1		propadiene			< 0.1	-
isobutene (A) % (M/M) < 0.1	4	1-butene			0.2	-
2-transbutene < 0.1		isobutene	-	% (m/m)	< 0.1	-
isopentane 0.1 - 2-cisbutene <0.1		2-transbutene	-		< 0.1	-
2-cisbutene < 0.1		isopentane	-			-
propene < 0.1		2-cisbutene				-
n-pentane < 0.1		propene			< 0.1	-
3-methylbutene-1 < 0.1		n-pentane			< 0.1	-
1,3-butadiene < 0.1		3-methylbutene-1			< 0.1	-
1,2-butadiene < 0.1		1,3-butadiene			< 0.1	-
< 0.1		1,2-butadiene	1		< 0.1	-
		above C ₅	1			-



5	Odour	PN-EN 589 + A1:2012 p. 6.3 app. A (A)	Dimensionless quantity	imperceptible	-
6	Water content test	PN-C-96008:1998 p. 4.4.5 (A)	Dimensionless quantity	not detected	-



Appendix 2:

		Results of analysis	6 (PP3/61/201	19)	
No	Parameter	Test standard	Unit	Result	Requirements for comparison
1	Sulphur content	ASTM D 6667-14 (A)	mg/kg	8.2	
2	Density at 15 °C	PN-EN ISO 8973:2000	km/m³	541.7	-
3	Absolute vapor pressure at temperature 20 °C	PN-EN ISO 8973:2000 PN-EN 589 + A1:2012 app. C	kPa	593	-
	Hydrocarbon composition				-
	methane			< 0.1 < 0.1	-
	ethane			1.3 0.8	-
	ethene			< 0.1 < 0.1	-
	propane	1		53.9	-
	propene	1		<0.1 <0.1	-
	isobutane			5.4	-
	cyclopropane			<0.1 <0.1	-
	n-butane			39.2 45.4	-
	propadiene			<0.1 <0.1	-
4	1-butene	PN-EN 27941:2015-12	% mol	0.2	-
4	isobutene	(A)	% (m/m)	<0.1 <0.1	-
	2-transbutene			<0.1 <0.1 <0.1	-
	isopentane	-		< 0.1	-
	2-cisbutene	-		< 0.1 < 0.1 < 0.1	-
	propene	-		< 0.1 < 0.1 < 0.1	-
	n-pentane	-		<0.1 <0.1 <0.1	-
	3-methylbutene-1	-		<0.1 <0.1 <0.1	-
	1,3-butadiene	1		<0.1 <0.1 <0.1	-
	1,2-butadiene	-		< 0.1	-
	above C ₃	-		<0.1 <0.1 <0.1	-



5	Odour	PN-EN 589 + A1:2012 p. 6.3 app. A (A)	Dimensionless quantity	imperceptible	-
6	Water content test	PN-C-96008:1998 p. 4.4.5 (A)	Dimensionless quantity	not detected	-



Appendix 3:

Results of chemical analysis

Parameter	Test method	Unit	Result	Requirements
1. amount C1			below 0.1	
2. amount C2	-		2.2	1
3. amount C3	PN-EN 27941:2015-12	% m/m	45.7	not
4. amount C4	7		51.3	standardized
5. amount C5	7		0.7	1
1. Methane			below 0.1	
2. Ethane	7		2.2	1
3. Ethene	7		below 0.1	1
4. Propane	7		44.4	1
5. Propene	7		1.3	1
6. i-butene	7		18.2	1
7. propadiene	7		below 0.1	1
8. n-butene	DN 5N 07041-0015 40	N	32.6	not
9. 2-trans-butene	PN-EN 27941:2015-12	% m/m	0.1	standardized
10. 1-butene	7		0.2	1
11. i-butene	7		0.2	1
12. cis-2-butene	7		below 0.1	1
13. 2,2-dimethylpropane	7		0.1	1
14. i-pentane	7		0.4	1
15. n-pentane	7		0.2	1
16. 1,3-butadiene	7		below 0.1	1
Motor octane number, MON	PN-EN 589+A1:2012 app. B	-	93.6	min. 89.0
Total dienes (including 1,3-butadiene)	PN-EN 27941:2015-12	% mol	below 0.1	max 0.5% mol
Hydrogen sulphide	PN-EN ISO 8819:2000	-	absent	absent
Total sulphur content	ASTM D 6667-14	mg/kg	29	max 50 mg/kg
Copper strip corrosion (1h at 40 °C)	PN EN ISO 6251:2001	-	class 1	class 1
Soluble residue	PN-EN 15471:2017-08	mg/kg	below 30	max 60 mg/kg
Relative vapor pressure at 40 °C	PN-EN ISO 8973:2000 + PN-EN 589+A1:2012 app.C	kPa	1005	max 1550 kPa
Odour	PN-EN 589+A1:2012 app. A	-	noticeable	noticeable
Temperature at which the relative vapor pressure is not less than 150 kPa	PN-EN ISO 8973:2000 + PN-EN 589+A1:2012 app.C	°C	-13.5	max 10 °C
Water content test	PN-EN 15469:2009	-	not detected	not to be detected
Density at 15 °C	PN-EN ISO 8973:2000	kg/m³	537.8	not standardized



Appendix 4:

Results of chemical analysis

Parameter	Test method	Unit	Result	Requirements
1. amount C1			below 0.1	
2. amount C2	-		1.5	1
3. amount C3	PN-EN 27941:2015-12	% m/m	51.9	not
4. amount C4			46.1	standardized
5. amount C5			0.5	1
1. Methane			below 0.1	
2. Ethane			1.5	1
3. Ethene			below 0.1	1
4. Propane			50.9	1
5. Propene			1.0	1
6. i-butene			18.1	1
7. propadiene			below 0.1	1
8. n-butene	DN EN 27041-2015 121	N (27.0	not
9. 2-trans-butene	PN-EN 27941:2015-121	% m/m	0.4	standardized
10. 1-butene			0.2	1
11. i-butene			0.2	1
12. cis-2-butene			0.2	1
13. 2,2-dimethylpropane			below 0.1	
14. i-pentane			0.3	1
15. n-pentane			0.2	1
16. 1,3-butadiene			below 0.1	1
Motor octane number, MON	PN-EN 589+A1:2012 app. B	-	94.0	min. 89.0
Total dienes (including 1,3-butadiene)	PN-EN 27941:2015-12	% mol	below 0.1	max 0.5% mol
Hydrogen sulphide	PN-EN ISO 8819:2000	-	absent	absent
Total sulphur content	ASTM D 6667-14	mg/kg	29	max 50 mg/kg
Study of corroding activity on the plate copper (1h at 40 °C)	PN EN ISO 6251:2001	-	class 1	class 1
A soluble residue	PN-EN 15471:2017-08	mg/kg	below 30	max 60 mg/kg
Relative vapor pressure at 40 °C	PN-EN ISO 8973:2000 + PN-EN 589+A1:2012 app.C	kPa	1003	max 1550 kPa
Odour	PN-EN 589+A1:2012 app. A	-	noticeable	noticeable
Temperature at which the relative vapor pressure is not less than 150 kPa	PN-EN ISO 8973:2000 + PN-EN 589+A1:2012 app.C	°C	-13.1	max 10 °C
Water content	PN-EN 15469:2009	-	not detected	not to be detected
Density at 15 °C	PN-EN ISO 8973:2000	kg/m³	534.5	not standardized



Appendix 5:

Results of chemical analysis

Results of chemical analysis			
Parameter	Result	Test method	Requirements
composition of hydrocarbons C1-C3			
1. amount C1	below 0.1		
2. amount C2	1.4	PN-EN 27941:2015-12	not standardized
3. amount C3	68.3	PN-EN 27941:2015-12	not standardized
4. amount C4	29.6		
5. amount C5	0.5		
1. Methane	below 0.1		
2. Ethane	1.4		
3. Ethene	below 0.1		
4. Propane	67.2]	
5. Propylene	1.1		
6. i-butane	11.9]	
7. propadiene	below 0.1]	
8. n-butane	17.0	PN-EN 27941:2015-12	not standardized
9. 2-trans-butene	0.1	PN-EN 27941.2013-12	not standardized
10. 1-butene	0.3		
11. i-butene	0.3		
12. cis-2-butene	below 0.1]	
13. 2.2-dimethylpropane	below 0.1		
14. i-pentane	0.3		
15. n-pentane	0.2]	
16. 1.3-butadiene	below 0.1]	
Motor octane number. MON	94.3	PN-EN 589+A1:2012 app. B	min. 89.0
Total dienes (including 1.3-butadiene)	below 0.1	PN-EN 27941:2015-12	max 0.5% mol
Hydrogen sulphide	absent	PN-EN ISO 8819:2000	lack
Total sulphur content	29	ASTM D 6667-14	max 50 mg/kg
Study of corroding activity on the plate copper (1h at 40 °C)	Class 1	PN EN ISO 6251:2001	class 1
A soluble residue	below 30	PN-EN 15471:2017-08	max 60 mg/kg
Relative vapor pressure at 40 °C	1132	PN-EN ISO 8973:2000 + PN-EN 589+A1:2012 app.C	max 1550 kPa
Odour	noticeable	PN-EN 589+A1:2012 app. A	noticeable
Temperature at which the relative vapor			
pressure	-10 (Type A)	PN-EN ISO 8973:2000 +	max -5 °C
is not less than 150 kPa		PN-EN 589+A1:2012 app.C	
Water content test	not detected	PN-EN 15469:2009	not found
Density at 15 °C . kg/m ³	523.6	PN-EN ISO 8973:2000	not standardized
Calorific value kJ/kg	46060	PN-C-96008:1998	min 45220



Appendix 6:

Results of chemical analysis

Parameter	Test method	Unit	Result	Requirements
Total sulphur content	ASTM D 6667-14	mg/kg	29	max 50 mg/kg
Copper strip corrosion (1h at 40 °C)	PN EN ISO 6251:2001	-	class 1	class 1

Appendix 7:

LINDE GAZ POLSKA SP.ZO.O. ul. prof. Michala Zyczkowskieg	Order numb Cylinder nu Cylinder ow	mber:	Page 1 of 1 103000572211/1 2727603 Linde cylinder
P-31-864 KRAKOW	Cylinder vol		50,00
	RTIFICATE Class 1 DIN EN ISO 6141		50 930 150 1500 150 2200 500 500 500 500 500 500 500 500 500
Components	Nominal value	Actual value	rel. uncertainty
propane butane	30,0 % Balance	30,5 %	± 2

Indications in percent and ppm are to be interpreted as ideal parts per volume. All indications of volume are related to STP (1013 mbar; 273, 15 K.) The results are certified on the basis of analytics

¹ expressed as the expanded measurement uncertainty (coverage factor k = 2)

Pressure [15º C	:	Min. storage temperature:	Not applicable
Contents:	21,002 kg	Min. pressure of utilization:	
Stability:	12 months	Rec. usage temperature:	10 °C - 30 °C
Valve outlet:	01 DV-TR	Net weight [Kg]:	21,002
Order:	315790914 / 000020		
Your Order:	PL1-12469		

Cylinder with dip tube and double valve.

Helium headpressure 15 bar



Appendix 8:

Translation of: REPORT NO. 33/TCH/2018-1

No	Parameter	Result	Test standard	Unit	Requirement
1	Sum C3	30.7	D11 C11		
2	Sum C4	69.3	PN-EN 29741:2015-12	%mol/mol	
3	<c3,>C4</c3,>	<0.1	29741.2015-12		
	Hydrocarbon composition				
	methane	<0.1]		
	ethane	<0.1]		
	ethene	<0.1]		
	propane	30.7	1		
	propene	<0.1	1		
	isobutane	<0.1	1		
	propadiene	<0.1	PN-EN 27941:2015-12 (A)		
4	n-butane	<0.1		% mol	
4	isobutene	<0.1		% moi	
	2-transbutene	<0.1			
	1-butene	<0.1			
	i-butene	<0.1			
	2-cis-butene	<0.1			
	2,2-dumethylpropane	<0.1	1		
	i-pentane	<0.1	1		
	n-pentane	<0.1	1		
	1,3-butadiene	<0.1	1		
5	Motor octane number (MON)	91	PN-EN 589+A1:2012	[-]	Min. 89.0
6	Total alkene content	<0.1	PN-EN 27941:2015-12	% mol	Max. 0.5
7	Hydrogen sulphide	Not detected	PN-EN ISO 8819:2000	[-]	Not to be detected
8	Total sulphur content	<0.1	ASTM D 6667- 14	mg/kg	50 (10 for reference LPG)
9	Copper strip corrosion (1h at 40°C)	Class 1	PN-EN ISO 6251:2001	[-]	Class 1
10	Soluble residue	<30	PN-EN 15471:2017-08	mg/kg	Max. 60



APPENDIX - COMPLEMENTARY STUDY: CHEMICAL ANALYSES OF THE AGED TWCS

0. ABSTRACT

Aged three-way catalytic converters (TWCs) were subjected to chemical analyses using advanced laboratory methods. The aim was to quantify quantitative and qualitative differences in the samples, which had been exposed to exhaust gas generated by light duty engines running on two fuel types (CNG, LPG) and with two different sulphur levels (Low, High). Vehicle tests showed that the CNG TWC conversion efficiency was sensitive to sulphur content, while this was not the case for the LPG TWC. At the end of the vehicle tests, it was assumed that this was due to a better desulphation process in the LPG TWC, due to differences in equivalence ratio at high load between the two powertrain types (lean burn with CNG and rich mixture with LPG). The purpose of this study was to check and provide evidence for this assumption. Significant differences between the TWCs' inlet and outlet faces were quantified, as well as differences between the edges of the monolith channels and the channels themselves. The TWCs dedicated to the CNG engine had significantly higher sulphur content than their LPG counterparts; however, no positive correlation between fuel sulphur level and TWC sulphur abundance was evidenced by the results. The different measured sulphur levels between the CNG and LPG TWCs are likely to support the fact that the desulphation process occurs more in LPG operating conditions than in CNG operating conditions. However, the fact that the high-sulphur CNG and the low-sulphur CNG TWCs show the same level of sulphur, whereas the high-sulphur CNG TWC lost much more conversion efficiency shows a non-systematic relationship between the sulphur content of the analysed TWCs and their conversion efficiency. Because of the fact that empirical findings did not directly link the TWCs' sulphur content with their conversion efficiency, the analysis remains inconclusive regarding its initial assumption of a better desulphation process occurring in the LPG TWC.

1. DESCRIPTION AND IDENTIFICATION OF THE OBJECTS TESTED

The objects of the tests were four original aftertreatment systems (three-way catalysts, TWCs) two of which were dedicated to the Lancia Y 0.9 Twin Air CNG application and two of which were dedicated to the Fiat Tipo 1.4 T-Jet LPG application. Within each sub-group, one TWC was denoted as 'Low S', and 'High S'. The four test objects are identified in Table 1.

Parameter	CNG Low S	CNG High S	TWC Low S	TWC High S
Exhaust aftertreatment system type	Close-coupled three-way catalytic converter		r catalyric conv	
Approx. monolith volume [dm³]	1.0		1.4	
Total PGM content [g/ft ³]; [g/dm ³]	200; 7.063		150;	5.30
PGM content (Pt:Pd:Rh)	0/192/8 (0:24:1)		0:145:5 (0:29:1)	
Intended application	Aftertreatment system for Lancia Ypsilon (Y) 0.9 Twin Air CNG		Aftertreatmer Fiat Tipo 1.	

Table 1Data of the test objects



Prior to their use in this study, the four test objects had previously been the subject of two experimental programmes had been carried out to assess the impact of fuel sulphur level on TWC emissions performance (conversion efficiency) [1], [2].

2. INTRODUCTION; OBJECTIVE OF THE TESTS

Physicochemical characterisations of aged aftertreatment for spark ignition engines (three-way catalysts - TWCs) were carried out in order to assess the impact of variable ageing conditions on the TWCs themselves. Results were obtained in order to provide further insight into the conversion efficiency of the TWCs, which had been previously assessed in separate studies. Two samples were taken from each test object (TWC), one representing the TWC inlet (upstream face) and the other representing the TWC outlet (downstream face). Each sample was analysed using the following combinations of techniques:

- SEM/EDS (Scanning Electron Microscopy with Energy Dispersive Spectroscopy)
- WD-XRF (Wavelength Dispersive X-ray Fluorescence) and ICP-OES (Inductively coupled plasma optical emission spectrometry).

As mentioned previously, two experimental programmes had been carried out to assess the impact of fuel sulphur level on the performance of the TWCs identified in Table 1 in eliminating regulated emissions. Overall, the results showed variable impacts of fuel sulphur on the test objects [1], [2]. The first study (on CNG fuel - [1]) focused on TWCs for a light-duty nominally stoichiometric CNG engine and showed a relatively clear, noteworthy deterioration in TWC conversion efficiency (i.e. an increase in regulated exhaust emissions) following ageing on CNG fuel of higher sulphur content. In the case of CNG, it was concluded that significant sulphur-driven deactivation (chemical poisoning) took place. Despite the relatively high temperatures and non-static exhaust gas conditions encountered during the highly intensive ageing procedure conducted on the CNG engine, it was adjudged that the TWC was not effectively purged of sulphur, or at least at a rate well below the rate at which sulphur accumulated. Differences in emissions performance (comparing low sulphur fuel to high sulphur fuel) increased over time. The second study (on LPG fuel - [2]) was conceptually very similar to the first, but performed on TWCs for a light-duty, nominally stoichiometric LPG application. That study showed a markedly different trend, namely that TWC performance showed essentially no significant response to LPG fuel sulphur level, even following extensive ageing. In the case of LPG, it was adjudged that the combination of high temperature and exhaust gas of highly variable composition originating from the engine used for ageing - from well below stoichiometry (i.e. $\lambda < 1$) at full load to fuel cut-off (i.e. $\lambda >>1$) - enabled passive regeneration of the TWC in the form of sulphur purging.

In order to test these hypotheses and further examine the implications, chemical characterisations were undertaken to investigate differences between the four test objects: CNG-dedicated TWC aged on low-sulphur fuel, CNG-dedicated TWC aged on high-sulphur fuel, LPG-dedicated TWC aged on low-sulphur fuel and LPG-dedicated TWC aged on high-sulphur fuel. Differences were examined according to three distinct (but related) comparison criteria, as shown in Table 2.

Impact of fuel sulphur level	CNG low S vs CNG high S		LPG low S vs	LPG high S
Intra-TWC differences	CNG low S: inlet vs outlet	CNG high S: inlet vs outlet	LPG low S: inlet vs outlet	LPG high S: inlet vs outlet
Impact of TWC specification and application/fuel-specific ageing	CNG (both TWCs) vs LPG		s LPG (both TWCs	;)

Table 2	Comparison	matrix for	the fou	r test objects
---------	------------	------------	---------	----------------



3. SCOPE AND METHODS OF THE TESTS

3.1 Preliminary sample preparation

All test objects (TWCs) had been stored, in their "as found" state (following ageing) at room temperature for at least 12 months. During that time, the TWCs' inlets and outlets were unobstructed, meaning that the monoliths were exposed to indoor ambient air, but with no direct exposure to exhaust gas.

The monoliths were removed from the aftertreatment system canning by carefully cutting open the metal casing. The monoliths were handled with care and stored in a clean environment.

Next, a section of each of the test objects was taken, corresponding to the upstream and downstream faces (inlet and outlet). A precision saw was used to cut perpendicular to the edge of the monolith, thus creating a narrow disk of approximate thickness 10 mm. This sample was cut in half: half was ground into a fine powder for use in the analyses focusing on the overall chemical composition (WD-XRF and ICP-OES), while the other half was further divided in order to expose the channels running through the sample (i.e. parallel to the direction of flow of the exhaust gas), thus enabling examination of those areas via scanning electron microscopy (SEM).

3.2 Sample preparation for WD-XRF and ICP-OES analysis

The samples mentioned in point 3.1 were thoroughly ground in a ceramic mortar then pressed in a manual press in order to convert them to a form suitable for use in the analytical equipment employed (and in accordance with BOSMAL/I-7-43/06).

4. DESCRIPTION AND RESULTS OF THE TESTS

4.1 Measuring equipment

The specifications of the measuring equipment are shown in Table 3.

Table 3 Data of measuring devices

Device Name Type		Identifying No.	Applicable BOSMAL test instruction
Analytical balance	Radwag	B/5341/BMC	-
ICP-OES spectrometer	Optima 8300	X/5407/BMC	BOSMAL/I-7-43/06
WD-XRF spectrometer	Rigaku ZSX Primus II	X/5403/BMC	BOSMAL/1-7-90/02

Note: see [1] and [2] for detailed descriptions of all equipment and measuring devices used in the ageing and emissions testing of the test objects carried out prior to this study.



4.2. Test results

4.2.1 WD-XRF and ICP-OES results for CNG TWCs

Results are shown in tabulated form below. The platinum group metals (PGM; Pt Pd and Rh) are shown in pure elemental form, while results base metals and other elements are shown on the basis of the element existing in the oxide form dominant at room temperature - i.e. Mg is shown as MgO; Al is shown as Al_2O_3 , etc.

Element	TWC 1 CNG LOW S IN	TWC 1 CNG LOW S OUT	TWC 2 CNG HIGH S IN	TWC 2 CNG HIGH S OUT		
Licinciti	Test results [%] (1)					
Pt	0.013	0.010	0.017	0.012		
Pd	1.2	1.0	0.89	0.79		
Rh	0.027	0.025	0.028	0.026		
Compound		Test resu	lts [%] ⁽²⁾			
Na ₂ O	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	0.14	0.10		
MgO	7.5	6.1	5.4	7.7		
Al ₂ O ₃	38.0	43.8	40.3	43.1		
SiO ₂	23.5	19.2	17.6	23.6		
P ₂ O ₅	1.3	0.16	1.7	0.43		
SO ₃	0.37	0.26	0.38	0.17		
K ₂ O	0.028	0.025	0.024	0.029		
CaO	0.48	0.13	0.63	0.38		
TiO ₂	0.55	0.57	0.51	0.51		
Mn ₂ O ₃	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾		
Fe_2O_3	0.64	0.52	0.59	0.56		
NiO	0.092	0.028	0.080	0.042		
CuO	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	0.042	< 0.02 ⁽³⁾		
ZnO	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	1.6	0.22		
SrO	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾		
Y ₂ O ₃	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾		
ZrO ₂	11.6	13.3	13.7	10.3		
BaO	2.3	2.0	2.4	2.1		
La_2O_3	1.3	1.3	1.5	1.1		
CeO ₂	7.9	9.5	10.0	7.0		
Pr ₆ O ₁₁	0.95	1.1	0.94	0.66		
Eu_2O_3	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾		
HfO ₂	0.47	0.54	0.57	0.35		
Nd ₂ O ₃	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾		

Table 4 Quantitative results from WD-XRF and ICP-OES for CNG TWCs

⁽¹⁾ mean result from WD-XRF and ICP-OES method

⁽²⁾ results from WD-XRF method

⁽³⁾ result under method limit of quantification

As the results relate to measurements made from directly comparable samples, comparisons within and between the test of object for a given fuel type can be made. The results of a numerical comparison of this type are shown in Tables 5 and 6.



Element	Relative comp	oarison of PGM abur objects (0%=num		from CNG test
	Inlet vs Inlet	Outlet vs Outlet	Low In vs Out	High In vs Out
Pt	27%	18%	26%	29 %
Pd	30%	23%	18 %	11%
Rh	4%	4%	8%	7%

Table 5 Comparison of quantitative PGM results from WD-XRF and ICP-OES for CNG TWCs.

Table 6 Comparison of quantitative elemental results from WD-XRF for CNG TWCs

Compound	Relative comparison of PGM abundances measured from CNG test objects (0%=numerically identical)					
Compound	Inlet vs Inlet	Outlet vs Outlet	Low: Inlet vs Outlet	High: Inlet vs Outlet		
Na₂O	N/D	N/D	N/D	29 %		
MgO	33%	23%	21%	43%		
Al ₂ O ₃	6%	2%	14%	7%		
SiO ₂	29%	21%	20%	34%		
P_2O_5	27%	92 %	156%	75%		
SO ₃	3%	42%	35%	55%		
K ₂ O	15%	15%	11%	21%		
CaO	27%	98 %	115%	40%		
TiO ₂	8%	11%	4%	0%		
Mn ₂ O ₃	N/D	N/D	N/D	N/D		
Fe ₂ O ₃	8%	7%	21%	5%		
NiO	14%	40%	107%	48%		
CuO	N/D	N/D	N/D	N/D		
ZnO	N/D	N/D	N/D	86%		
SrO	N/D	N/D	N/D	N/D		
Y ₂ O ₃	N/D	N/D	N/D	N/D		
ZrO ₂	17%	25%	14%	25%		
BaO	4%	5%	14%	13%		
La_2O_3	14%	17%	0%	27%		
CeO ₂	23%	30%	18%	30%		
Pr ₆ O ₁₁	1%	50%	15%	30%		
Eu ₂ O ₃	N/D	N/D	N/D	N/D		
HfO ₂	19%	43%	14%	39%		
Nd_2O_3	N/D	N/D	N/D	N/D		



Generally speaking, the CNG test objects showed relatively high differences between the inlet and outlet PGM levels. However, the absolute levels for Pt are very low, meaning very small absolute differences equate to large relative differences. Comparisons for other compounds showed variable trends, with large relative differences observed in some cases (notably for phosphorous). The main assumed source of phosphorous is lubricating oil (and possibly fuel contaminants), yet the same oil type meeting the ACEA A3 standard was used for ageing (and indeed testing) of the test objects. However, the low absolutely abundances of many of the compounds quantified should be borne in mind when considering results of this type. Certain compounds with higher abundances showed relatively modest differences for both intra- and intersample comparisons, including the most abundant compound, Al₂O₃. Lacking a control (i.e. an unaged TWC of identical type), it was not possible to determine to what extent the observed differences resulted from inherent differences between the TWCs (and indeed their inlet and outlet faces), as opposed to fuel-specific ageing effects. In this context, and in light of the CNG emissions trends presented in [1], the lack of an overall positive correlation between CNG sulphur level and the measured abundance of sulphur in the samples would appear to be a potentially significant finding warranting further investigation.

4.2.2 WD-XRF and ICP-OES results for LPG TWCs

Results are shown in tabulated form below. As mentioned in the previous section, PGM are shown in pure elemental form, while results base metals and other elements are shown as oxides.



Element	TWC 3 LPG LOW S IN	TWC 3 LPG LOW S OUT	TWC 4 LPG HIGH S IN	TWC 4 LPG HIGH S OUT		
Ltement	Test results [%] ⁽¹⁾					
Pt	0.017	0.017	0.017	0.016		
Pd	0.67	0.56	0.67	0.61		
Rh	0.021	0.015	0.016	0.015		
Compound		Test res	ults [%] ⁽²⁾			
Na ₂ O	0.22	0.080	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾		
MgO	2.8	4.4	3.7	3.9		
Al ₂ O ₃	51.5	52.8	52.1	54.7		
SiO ₂	9.3	14.5	11.5	12.3		
P_2O_5	2.5	0.20	2.0	0.070		
SO ₃	0.14	0.063	< 0.02 ⁽³⁾	0.058		
K ₂ O	2.2	0.16	0.088	0.045		
CaO	0.35	0.075	0.15	0.050		
TiO ₂	0.27	0.36	0.27	0.34		
Mn ₂ O ₃	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾		
Fe ₂ O ₃	0.82	0.72	0.80	0.70		
NiO	0.031	0.030	0.036	0.033		
CuO	0.10	< 0.02 ⁽³⁾	0.082	< 0.02 ⁽³⁾		
ZnO	1.4	0.27	< 0.02 ⁽³⁾	0.091		
SrO	0.066	0.075	0.10	0.080		
Y ₂ O ₃	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	0.017	0.016		
ZrO ₂	10.6	10.2	11.0	10.7		
BaO	3.1	3.2	3.4	2.9		
La_2O_3	0.65	0.60	0.69	0.56		
CeO ₂	10.7	9.5	10.7	10.3		
Pr ₆ O ₁₁	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾		
Eu ₂ O ₃	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾	< 0.02 ⁽³⁾		
HfO ₂	0.48	0.48	0.50	0.48		
Nd_2O_3	1.2	1.1	1.2	1.1		

Table 7 Quantitative results from WD-XRF and ICP-OES for LPG TWCs

⁽¹⁾ mean result from WD-XRF and ICP-OES method
 ⁽²⁾ results from WD-XRF method
 ⁽³⁾ result under method limit of quantification

Numerical comparisons of the results are shown in Tables 8 and 9.



Element	Relative comp	oarison of PGM abui objects (0%=num		from LPG test
	Inlet vs Inlet	Outlet vs Outlet	Low In vs Out	High In vs Out
Pt	0%	6%	0%	6%
Pd	0%	9 %	18%	9 %
Rh	27%	0%	33%	6%

Table 8 Comparison of quantitative PGM results from WD-XRF and ICP-OES for LPG TWCs.

Table 9Comparison of quantitative elemental results from WD-XRF for LPG TWCs.

Compound	Relative com	parison of PGM abun objects (0%=nume		from LPG test
compound	Inlet vs Inlet	Outlet vs Outlet	Low: Inlet vs Outlet	High: Inlet vs Outlet
Na₂O	N/D	N/D	93%	N/D
MgO	28%	12%	44%	5%
Al ₂ O ₃	1%	4%	2%	5%
SiO ₂	21%	16%	44%	7%
P_2O_5	22%	96 %	170%	97 %
SO ₃	N/D	8%	76%	N/D
K ₂ O	185%	112%	173%	49 %
CaO	80%	40%	129 %	67%
TiO ₂	0%	6%	29%	26%
Mn ₂ O ₃	N/D	N/D	N/D	N/D
Fe ₂ O ₃	2%	3%	13%	13%
NiO	15%	10%	3%	8%
CuO	20%	N/D	N/D	N/D
ZnO	N/D	99%	135%	N/D
SrO	41%	6%	13%	20%
Y ₂ O ₃	N/D	N/D	N/D	6%
ZrO ₂	4%	5%	4%	3%
BaO	9%	10%	3%	15%
La_2O_3	6%	7%	8%	19%
CeO ₂	0%	8%	12%	4%
Pr ₆ O ₁₁	N/D	N/D	N/D	N/D
Eu ₂ O ₃	N/D	N/D	N/D	N/D
HfO ₂	4%	0%	0%	4%
Nd_2O_3	0%	0%	9%	8%



Overall, the LPG test objects showed somewhat better agreement in terms of PGM levels compared to the CNG test objects, as regards both intra- and inter-TWC comparisons. As with the CNG test objects, comparisons for other compounds showed variable trends, with large relative differences observed in some cases (phosphorous, potassium, calcium and zinc). As in the case of the CNG test objects, the same oil type, which met the ACEA A3 standard, was used for ageing (and indeed testing) of the test objects. However, the low absolute abundances of many of the compounds quantified should be borne in mind when considering results of this type. As expected, compounds with higher abundances showed smaller differences in intra- and inter-sample comparisons. Due to the lack of control measurements, no concrete conclusions can be drawn on the causes and origins of the observed differences in abundance. However, the lack of an overall positive correlation between fuel sulphur level and observed sample sulphur abundance is a finding of potential significance.

4.2.3 SEM results for CNG TWCs

SEM analyses were carried out on samples from the inlet and outlet faces, with sample preparation as described in section 3.1, with the obvious exclusion of the grinding and homogenisation step, since the samples were analysed from the structural point of view, with a clear distinction made between the monolith channels themselves and the intersection where the channel was bounded by the channel walls. The aforementioned location types are hereafter referred to as 'Channel' and 'Edge', respectively.

SEM images of the CNG test objects are shown in <u>Annex 1</u>. To serve as a guide, a sample result set is shown in Figure 1.

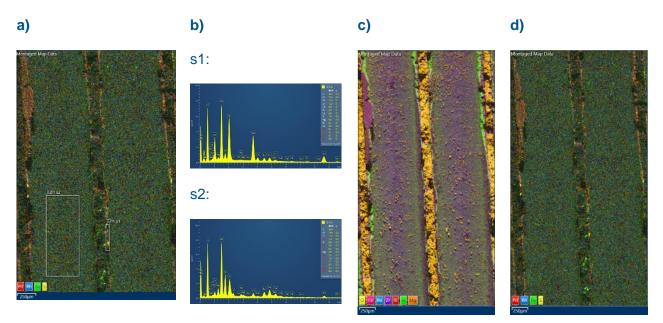


Figure 1 Sample SEM result set for a single location. a) map showing the location of indicated areas 1 and 2 (s1, s2); b) spectrograms for areas s1, s2; c) intensity-based map; d) map showing four chosen elements (Pd, Rh, S, Fe).



Each sample (inlet or outlet) was mapped 5 times; each map (panel a) in the figure above) contained a minimum of 2 indicated areas (s1, s2), in some cases supplemented by examination of a further area (s3) at the SEM operator's discretion. Thus, each sample was subject to a minimum of 10 measurements. The sites at the 5 locations (s1, s2) represented the edges and channels, with those two sites differentiated by eye, making use of the characteristic form of the wall and the elements associated with its core and boundaries to identify edges (refer to the intensity-based map - Figure 1, panel c)); the channel was simply the area between two edges, i.e. within the walls.

Panel b) presents the quantitative spectrograms for s1, s2. In panel c), the intensity-based map shows the distribution of elements with the highest abundances, which are dominated by base metals and oxygen. For that reason, panel d) shows the same map showing the four selected elements of primary interest in the context of this study: Pd and Rh, being the PGM species present in the test objects according to the manufacturer's specification; S, as the focus on the investigations and the independent variable in the ageing studies; and Fe as a tracer species for potential contamination introduced by material originating from engine wear and/or steel saw blades used in sample preparation. Regarding the final point, it can be stated that no direct evidence of any ferrous contamination was observed in any of the samples; however, exhaustive investigation of this aspect would require a control in the form of a sample which had not been exposed to neither engine ageing, nor to ferrous saw-blades.

4.2.4 SEM results for LPG TWCs

SEM analyses were carried out in an identical fashion to those performed on the CNG samples, as described in the previous section.

SEM images of the LPG test objects are shown in <u>Annex 2</u>. As with the CNG samples, it can be stated that no direct evidence of any ferrous contamination was observed.

5 GRAPHICAL COMPARISONS OF WD-XRF RESULTS; FURTHER DISCUSSION

The following figures present comparisons of the results presented in Tables 4 and 7, together with brief discussions of key observations. Results for compounds for which the measured value was below the limit of quantification are not shown in the figures.

As the desired functionality of a TWC is provided - above all - by PGM, the measured abundances of PGM from the test objects can be considered among their most fundamental characteristics. Results of that type are shown graphically in Figures 2 and 3 for the CNG test objects.



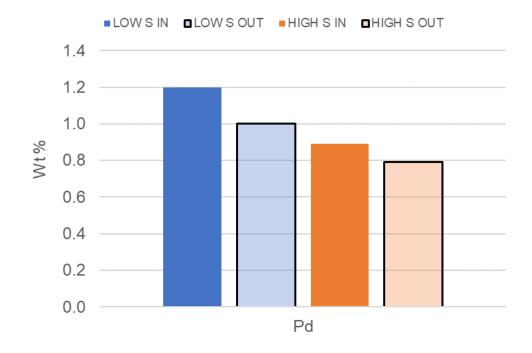
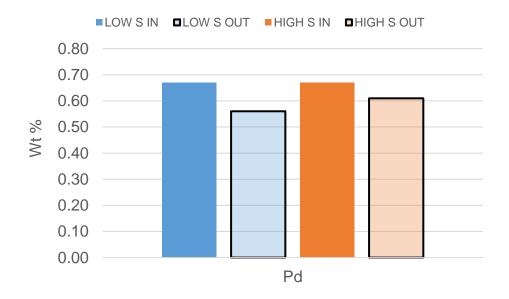


Figure 2 Pd abundance in the CNG test objects, measured by WD-XRF.



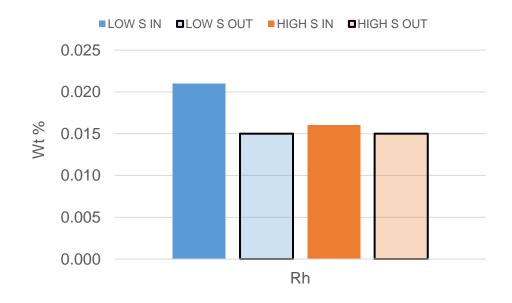
Figure 3 Rh abundance in the CNG test objects, measured by WD-XRF.





Figures 4 and 5 show equivalent results for the LPG test objects.



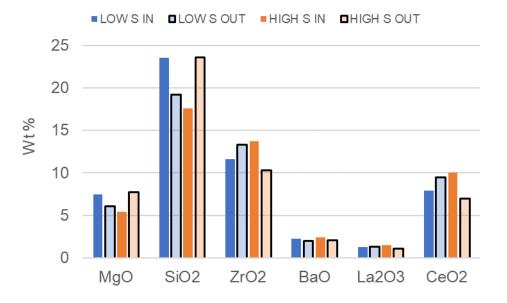




As the figures above show, a general trend could be observed for higher Pd and Rh abundances at the inlet than out the outlet of a given test object. However, the results suggest that in some cases differences in abundance were present between test objects of the same type. For example, the Pd abundances in the CNG test objects were measured as being lower in the case of the High unit (Figure 2). The same can be said for the case of Rh for the inlet sample of the LPG units (Figure 5). These measured differences, while rather large in relative terms, are relatively modest in absolute terms and may not necessarily be fully representative of the composition of the test objects.



Base metals including Al, Ce, La, Ba and Zr also play important roles in co-catalysis, oxygen storage, general promotion, structural support and overall stabilisation [3]; results for those five elements, plus Si and Mg are shown in the figures below; Al is shown separately due to its high abundance. Results of that type are shown graphically in Figures 6 and 7 for the CNG test objects.





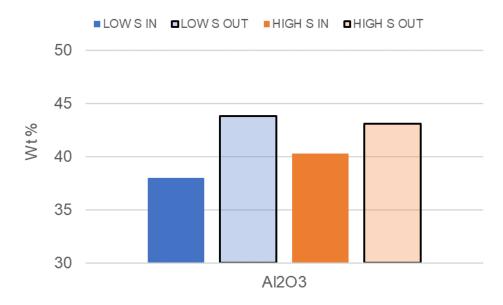
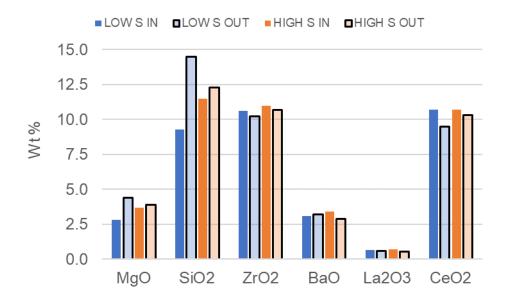


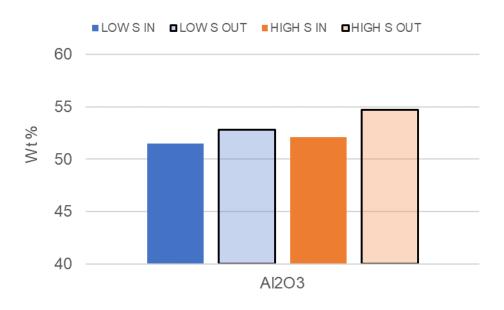
Figure 7 Abundance of Al₂O₃ in the CNG test objects, measured by WD-XRF.





Figures 8 and 9 show the same results for the LPG test objects.

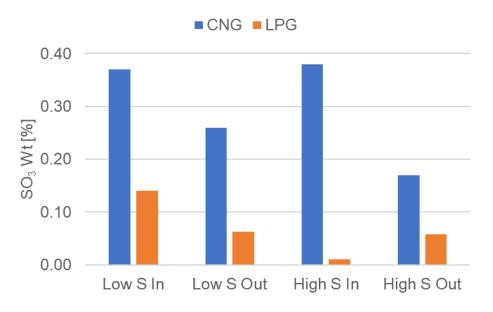






As the independent variable in the TWC ageing studies ([1], [2]) was fuel sulphur content, and as both PGM and base metals present in TWCs are well-known to suffer adverse impacts to their functionality caused by sulfation [3], the measured abundance of sulphur in the test objects was a key point of interest in this study. Results of that type are shown graphically in Figure 10. As with the distribution of PGM, it should be recalled that the measured abundances from the inlet and outlet face samples are not necessarily representative of the holistic value applicable to the entire monolith.



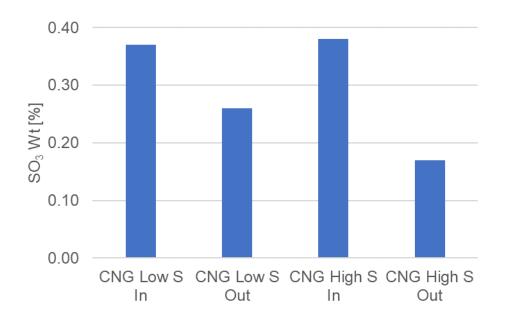




As Figure 10 clearly shows, the CNG test objects' sulphur abundance was much higher than that of the LPG test objects, with differences being 264-412% for direct comparisons of all samples except for CNG/LPG High S Inlet, for which the measured difference was an extreme outlier (38fold). With the exception of the aforementioned outlying result, a finding of this type was broadly expected, due to the test objects' emissions performance following ageing (see [2] for a discussion of this aspect). As regards the source of sulphur as an input to the system, the fuels used in [1] and [2] featured sulphur levels of a comparable order of magnitude; the total quantity of fuel consumed is not identical for the CNG engine and LPG engine employed in the ageing studies, but again the total mass of fuel consumed can be considered to be of the same order of magnitude, since the energy demand of the ageing procedures used on the engines showed limited differences; furthermore, the number of cycle repetitions was identical for both studies/engines.

In order to allow visual comparison, the two sets of results are plotted separately below in Figures 11 and 12.







For the CNG test objects, there was a clear tendency for the inlet sample to have a higher sulphur abundance than the outlet. The impact of fuel sulphur level was variable: the inlet abundances were essentially identical (difference <3%), thus giving no correlation between that parameter and the fuel sulphur level. The outlet abundances revealed an in verted correlation, since the sample aged on high sulphur fuel showed a lower abundance of that element (difference 35%).

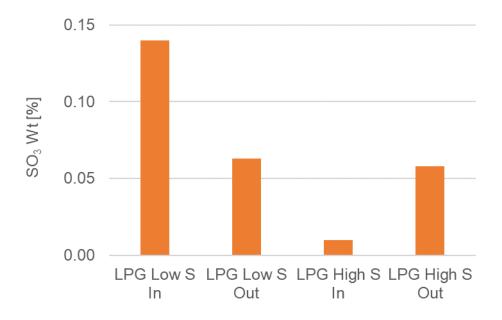


Figure 12 Sulphur abundance in all samples from LPG test objects, measured by WD-XRF.



For the LPG test objects, there was a large difference between the inlet abundances (55%), again showing an inverse correlation with the fuel sulphur level, as was the case with the CNG units. While the outlet abundances were similar for both LPG test objects (difference <8%), the inlet abundance of the LPG High S unit was at a very low level, showing different behaviour than the other three test objects, for which S_{inlet} - S_{outlet} in all cases.

While WD-XRF results are obtained from homogenised samples which present a holistic representation of the overall chemical composition of the cross section, the inlet and outlet samples are not necessarily representative of the entire volume of the monolith from which they were taken. Especially for TWCs which have been subject to extended high-temperature ageing (as was the case with all four test objects examined in this study), the formation of cracks and other small-scale mechanical defects may lead to uneven flow through the monolith, since the exhaust gas stream will have a tendency to follow the path of least resistance. In light of the possibility the aforementioned effects contributing (at least somewhat) and their evident implications for emissions performance, it can be stated that further analysis of additional samples taken from the inlet and outlet zones, as well as intermediate points, would significantly reduce the uncertainty associated with the measured abundances. (Note however, that quantitative assessments of sulphur abundance obtained via the SEM method are also available from this study and are indeed presented in the following section of this report.)

When reviewing the results for abundance of sulphur, an important consideration is the baseline level of that element which was present in the test objects before any ageing was carried out and to what degree this might differ between the inlet and the outlet and between test objects. The abundance of sulphur atoms in pristine (unaged) TWCs was not assessed in this study, since all test objects had been aged, as described previously. Despite conducting exhaustive enquiries, it was not possible to obtain quantitative S abundances for the test objects, nor for other TWCs of similar type. It was, however, confirmed that while industry-standard ceramics (cordierite) do not include S atoms in their idealised structures [4], [5], the raw mineral sources that are used to produce monoliths and other elements of the TWC typically include low but measurable quantities of sulphur. Various additives used prior to the extrusion process [4] may also contain at least some sulphur; a certain proportion of the sulphur from the aforementioned sources is inevitably carried over into the final product. High-temperature kiln firing - the final stage of the monolith manufacturing process [4] - removes a range of impurities and can be assumed to result in all remaining S atoms present in the fired monolith being in a form which will not have a detrimental impact on TWC performance. That is to say, a certain abundance of S atoms will remain in the monolith, not present in the elemental form, but within compounds which have survived the kiln firing process and are therefore by definition stable at very high temperatures. The quantitative abundance and qualitative distribution of S atoms may vary somewhat between TWCs, although TWCs of the same type, from the same manufacturer and originating from identical or closelyspaced production batches are likely to have at least similar levels and distributions of S atoms. However, the same assertion cannot be made with the same degree of confidence when comparing monoliths of different type, especially where they were produced some time apart and possibly by different manufacturers. As the experimental work performed in this study (and in the ageing studies themselves [1], [2]) did not include analysis of pristine (unaged) TWCs, it is not possible to comment any further on the observed tendencies for sulphur abundances in the test objects. Specifically, the question as to what proportion of the measured sulphur abundance present in the test objects prior to any ageing being carried out cannot be answered without further measurements carried out on equivalent test objects or supply of such data from a third party.



6

GRAPHICAL COMPARISONS OF SEM RESULTS; FURTHER DISCUSSION

While SEM results may be understood as being primarily qualitative in nature, the mapping process generates quantitative data, which may be used to examine elemental abundances in the areas examined. As each sample was mapped 5 times, and as each map area contained at least 2 indicated areas, quantitative data obtained from those areas could be collated and processed to produce a mean measured abundance, together with associated uncertainty. The division of sites into edge and channel categories was maintained. Based on this approach, quantitative plots were produced based on data obtained via SEM analysis. In analysing these results, it is important to recall certain points:

- the relatively limited number of measurements and the relatively high uncertainty associated with each measurement reflected in the magnitude of the error bars in the plots below,
- the non-holistic nature of the SEM technique and the arbitrary choice of the indicated areas,
- the potential for strong shielding effects owing to limited electron penetration through the washcoat,
- the fact that SEM response is proportional to atomic mass (and is therefore significantly weaker for light elements such as sulphur than for PGM).

Figures 13 and 14 show results for the CNG test objects, separated according to the nature of the indicated sites (edge/channel), as well as by sample type (inlet/outlet).

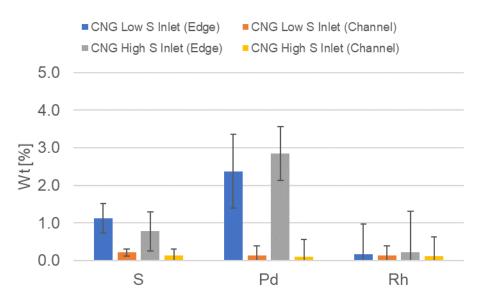


Figure 13 Abundances S, Pd and Rh in the inlet samples of the CNG test objects, measured by SEM and divided by nature of site.



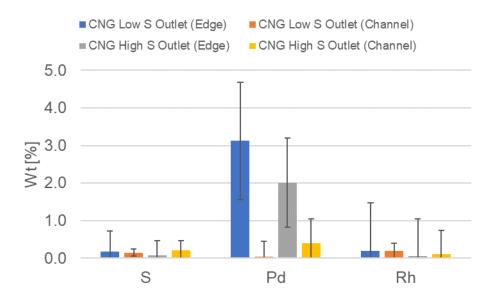


Figure 14 Abundances S, Pd and Rh in the outlet samples of the CNG test objects, measured by SEM and divided by nature of site.

Due to the large disparity in abundance between Pd and Rh (and S, in certain cases), the same plots are shown below without palladium.

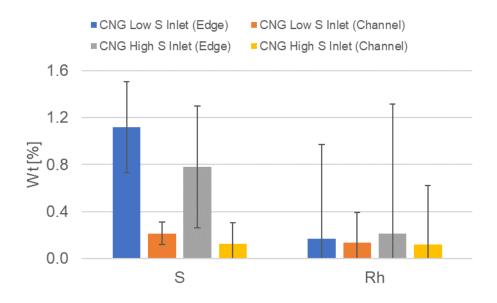


Figure 15 Abundances S and Rh in the inlet samples of the CNG test objects, measured by SEM and divided by nature of site.



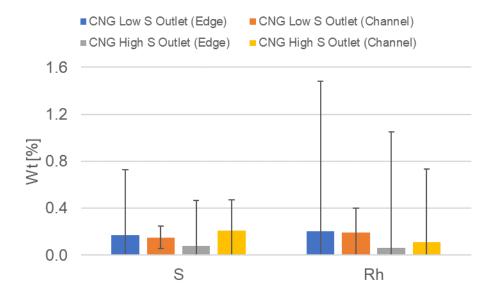


Figure 16 Abundances S and Rh in the outlet samples of the CNG test objects, measured by SEM and divided by nature of site.

A fundamental observation relates to the fact that calculated uncertainty values are for the most part very high - often significantly higher than the mean value of the measurements. For comparisons of abundances of PGM and S between test objects (i.e. Low vs High), the WD-XRF results are considered a much more reliable source, although the holistic abundance values generated by that technique are unable to distinguish between edges and channels. Differences in abundance were observed between edges and channels; some such differences appeared to be significant, despite the significant uncertainty associated with each measurement (and each calculated mean value). Abundances of Pd were much higher at edge sites than channel sites; for S this effect was in evidence at the inlet, but for Rh at the inlet and Rh and S at the outlet the low abundances of those elements and the very high uncertainty mean that no real trend is discernible.

As the co-occurrence of sulphur on PGM was a principle point of interest, and since quantitative SEM data were available for S, Pd and Rh, those data were co-plotted, again divided by edge/channel and inlet/outlet. For reasons of clarity, the datapoints are shown without error bars.



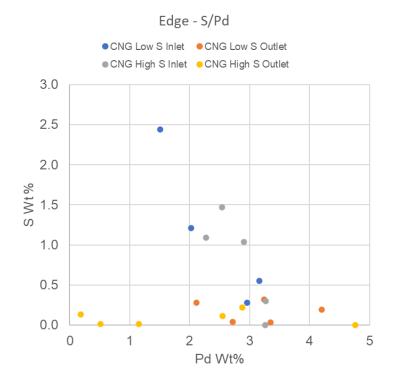


Figure 17 Co-plot of S and Pd abundances for the edge sites of samples from the CNG test objects, measured by SEM.

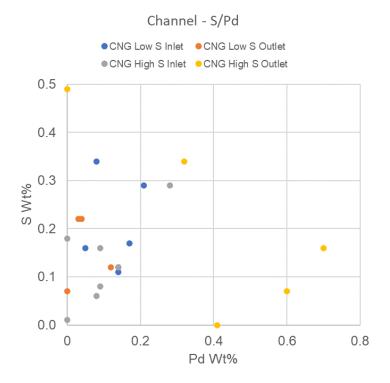


Figure 18 Co-plot of S and Pd abundances for the channel sites of samples from the CNG test objects, measured by SEM.



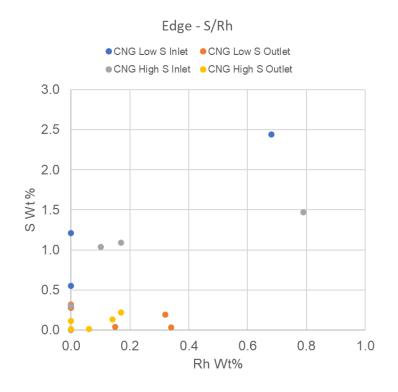


Figure 19 Co-plot of S and Rh abundances for the edge sites of samples from the CNG test objects, measured by SEM.

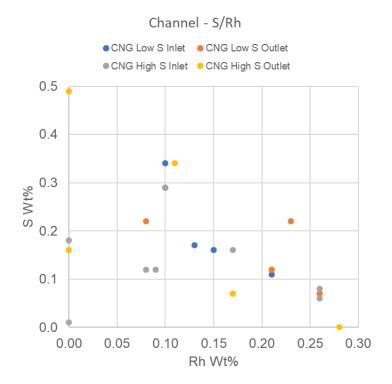


Figure 20 Co-plot of S and Rh abundances for the channel sites of samples from the CNG test objects, measured by SEM.



As the figures above show, the main difference between edge and channel sites was in terms of the abundances of both Pd/Rh and S, which were much higher at edge sites. In all cases, no clear correlational trend between the abundance of S and Pd or Rh was apparent at edge or channel sites, especially when considering the uncertainty associated with the measurements (not shown in the plots).

Equivalent plots for the SEM measurements performed on the LPG test objects are shown in Figures 21-28.

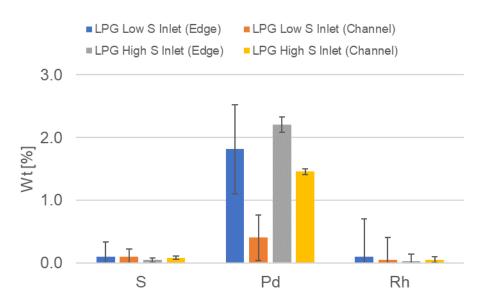


Figure 21 Abundances S, Pd and Rh in the inlet samples of the LPG test objects, measured by SEM and divided by nature of site.

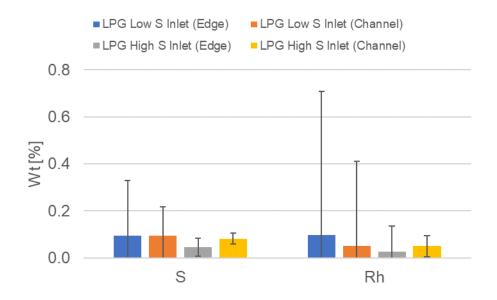


Figure 22 Abundances S and Rh in the inlet samples of the LPG test objects, measured by SEM and divided by nature of site.



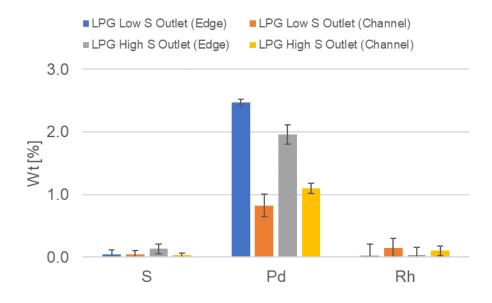


Figure 23 Abundances S, Pd and Rh in the outlet samples of the LPG test objects, measured by SEM and divided by nature of site.

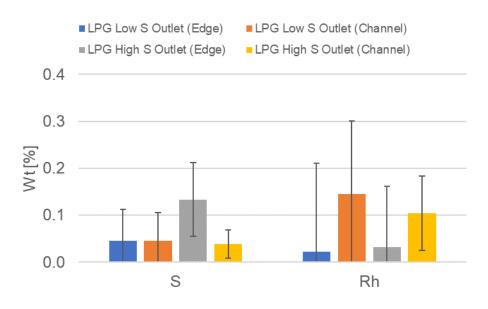


Figure 24 Abundances S and Rh in the inlet samples of the LPG test objects, measured by SEM and divided by nature of site.



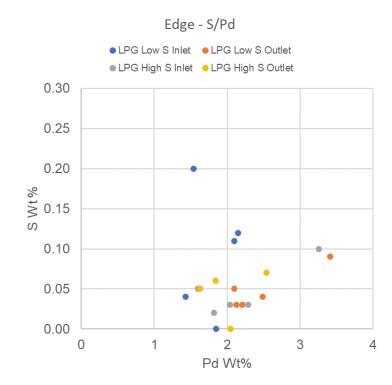
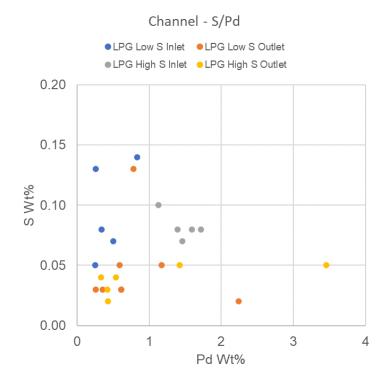


Figure 25 Co-plot of S and Pd abundances for the edge sites of samples from the LPG test objects, measured by SEM.







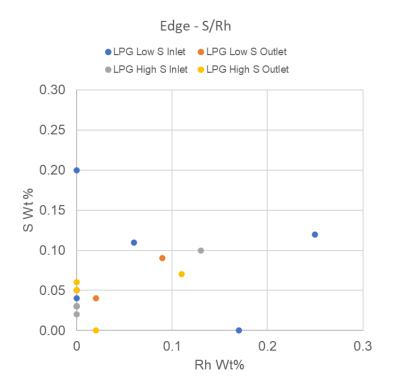


Figure 27 Co-plot of S and Rh abundances for the edge sites of samples from the LPG test objects, measured by SEM.



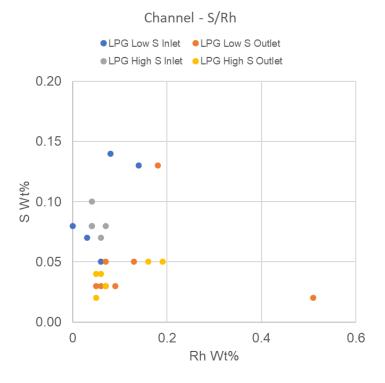


Figure 28 Co-plot of S and Rh abundances for the channel sites of samples from the LPG test objects, measured by SEM.

The observed tendencies for the LPG test objects were, generally speaking, similar to those observed for the CNG test objects, as described above. Only Pd showed edge/channel differentiation considered likely to be significant. The lack of any significant correlation regarding co-location of S and Pd/Rh was apparent from the co-plots of results for those elements.

7 FINAL CONCLUSIONS

Aged three-way catalytic converters (TWCs) were subjected to chemical analyses using advanced laboratory methods. The aim was to quantify quantitative and qualitative differences in the samples, which had been exposed to exhaust gas generated by light duty engines running on two fuel types (CNG, LPG) and with two different sulphur levels (Low, High). Vehicle tests showed that the CNG TWC conversion efficiency was sensitive to sulphur content, while this was not the case for the LPG TWC. At the end of the vehicle tests, it was assumed that this was due to a better desulphation process in the LPG TWC, due to differences in equivalence ratio at high load between the two powertrain types (lean burn with CNG and rich mixture with LPG). The purpose of this study was to check and provide evidence for this assumption. Investigations using WD-XRF, ICP-OES and SEM techniques permitted quantification of certain observable differences between the test objects and between the two samples taken from each test object. However, trends were not consistent in all cases. While the CNG test objects showed much higher abundances of sulphur than their LPG counterparts, the key parameter of interest, namely TWC sulphur content, was not observed to correlate with the sulphur level of the fuel used for ageing (i.e. high vs low). This finding is unexpected, especially given the fact that for the CNG TWCs, a significant accumulation of sulphur was expected, as attested to by the emissions results [1]. The possibility of removal of sulphur atoms from the test object during the ageing process (and even during emissions testing) is mentioned in [1] and discussed in detail in [2]. A lack of quantitative information on the distribution of sulphur atoms throughout the test objects' entire volume - as well as on the sulphur content of the test objects in their pristine state - currently precludes further analysis of this point. The limited number of sites chosen for the SEM analyses affects the statistical significance of the quantitative SEM results and imposes certain limitations on the qualitative conclusions which can be drawn from the SEM images and accompanying data. Quantitative SEM results where the measured weight concentration was zero (or very close to zero) mean that the uncertainty of



the mean value taken from the limited number of observations is high and observed differences are, in many cases, very unlikely to be statistically significant. Thus, considering the overall statistical significance of the quantitative SEM results, as well as the inherent limitations of the SEM technique concerning sensitivity to elements of lower atomic mass (such as sulphur), no definitive conclusions could be drawn regarding the potential existence of a significant correlation concerning the co-occurrence of S and Pd (or Rh). Further factors contributing to this are: shielding effects, the limited depth of electron penetration and the lack of a control (i.e. analysis of an unaged TWC of each type).

Certain changes which may have occurred in the test objects during the ageing process, which can have an impact on emissions conversion efficiency, would not necessarily have been revealed by the methods employed in this study. This category includes very small-scale changes such as reductions in available surface area suffered by metal oxides, and certain forms of atomic migration and rearrangement, not limited to processes such as sintering and clustering (see [5] for a recent review; see also [6]), as well as modifications to the electrical properties of the TWC's active layer [3]. Such phenomena (or lack thereof) may have had appreciable impacts on the performance of the test objects during their respective emissions testing programmes ([1], [2]) and may result from the complex interactions between fuel type, specific ageing conditions and indeed fuel sulphur level. Data relating to changes of the aforementioned type in the test objects could not be obtained in this study for reasons relating to the methods used, the number of observations and the lack of control measurements.

The different measured sulphur levels between the CNG and LPG TWCs are likely to support the fact that the desulphation process occurs more in LPG operating conditions than in CNG operating conditions. However, the fact that the high-sulphur CNG and the low-sulphur CNG TWCs show the same level of sulphur, whereas the high-sulphur CNG TWC lost much more conversion efficiency shows a non-systematic relationship between the sulphur content of the analysed TWCs and their conversion efficiency. Because of the fact that empirical findings did not directly link the TWCs' sulphur content with their conversion efficiency, the analysis remains inconclusive regarding its initial assumption of a better desulphation process occurring in the LPG TWC.

8. REFERENCES

[1] Concawe Report no. 6/20, dated 17.04.2020, "Three-way catalyst performance using natural gas with two different sulphur levels," available at https://www.concawe.eu/publication/three-way-catalyst-performance-using-natural-gas-with-two-different-sulphur-levels/.

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[4] Govender, S. and Friedrich, H.B., "Monoliths: A Review of the Basics, Preparation Methods and Their Relevance to Oxidation," Catalysts, 2017, 7, http://dx.doi.org/10.3390/catal7020062.

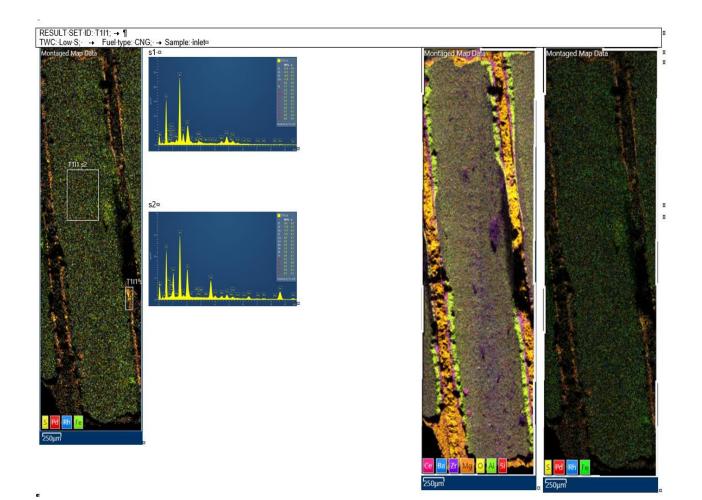
[5] Rood, S., et al., "Recent Advances in Gasoline Three-way Catalyst Formulation: a Review," Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, 2020, 234(4), http://dx.doi.org/10.1177/0954407019859822.

[6] Donlon, W.T., et al., Automotive Applications of Scanning and Transmission Electron Microscopy, Industrial Applications of Electron Microscopy, 1st ed., 2002, CRC Press, USA, ISBN: 9780429222429.

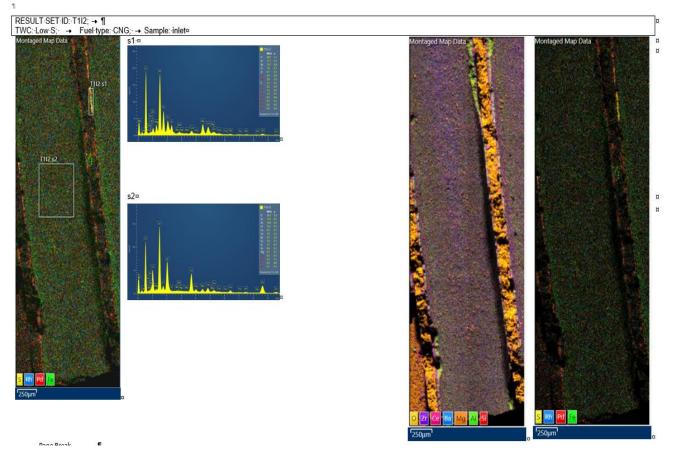


Annex 1

SEM result sets for CNG test objects (TWCs 1 and 2)

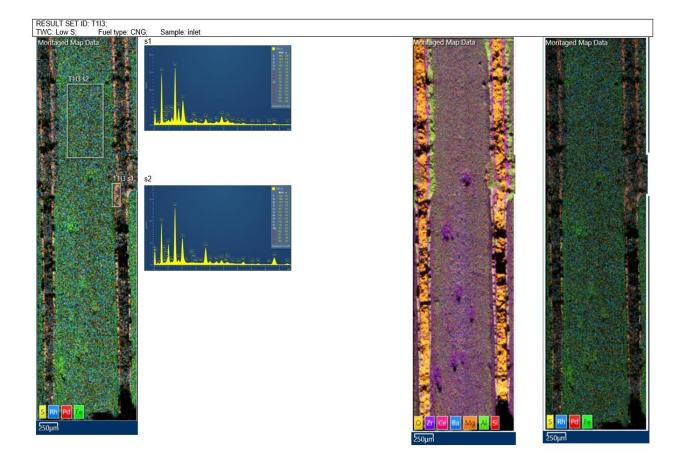






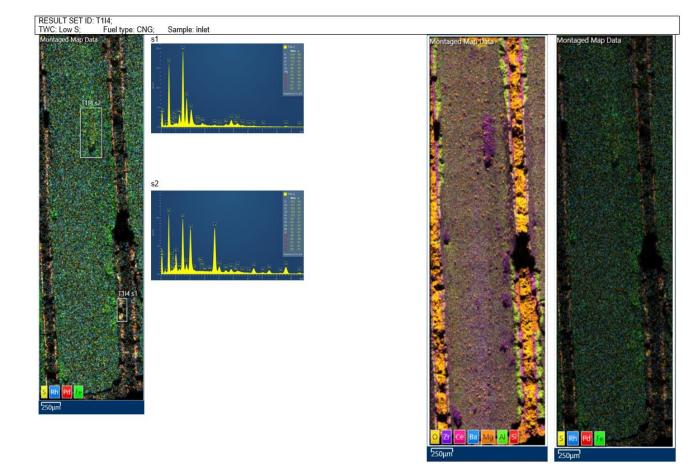
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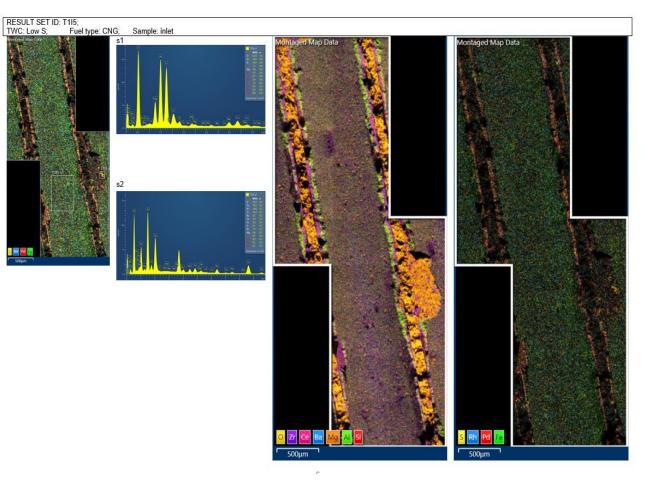






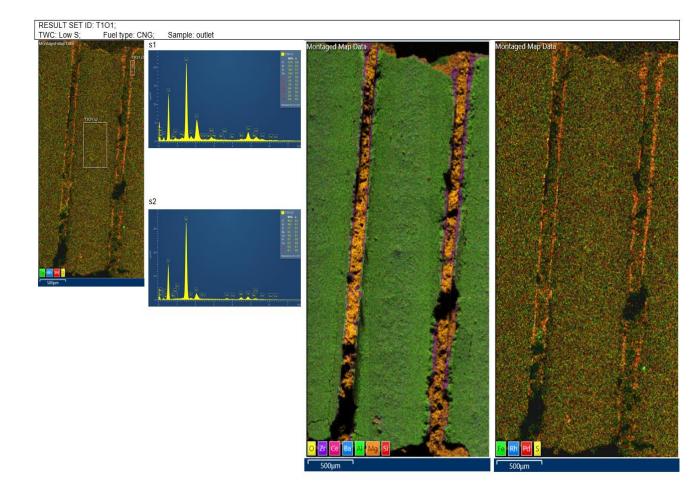






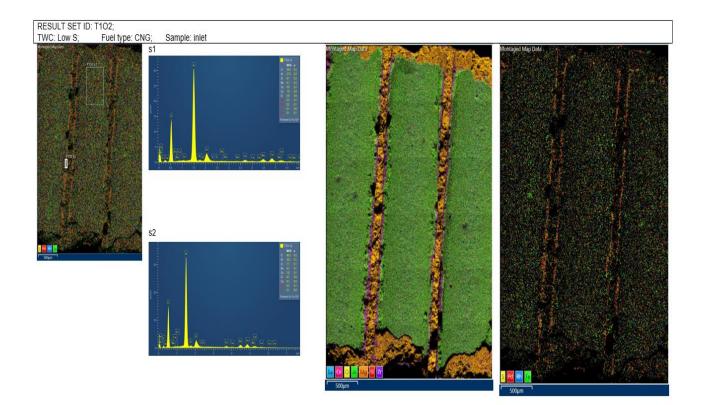




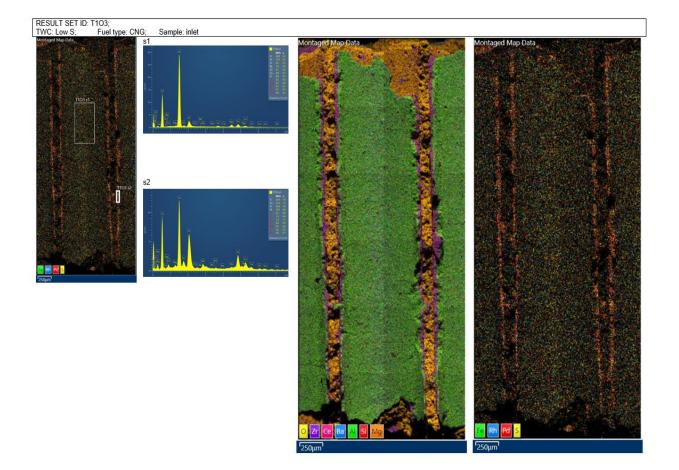






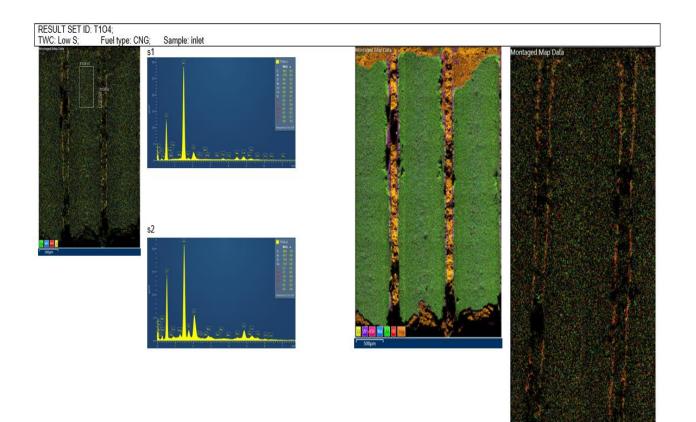






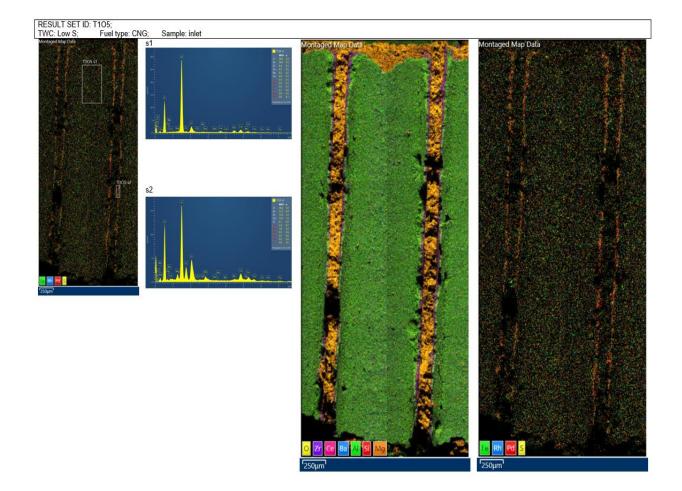






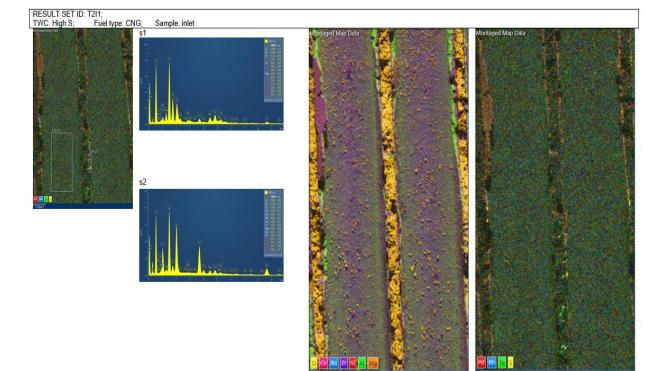




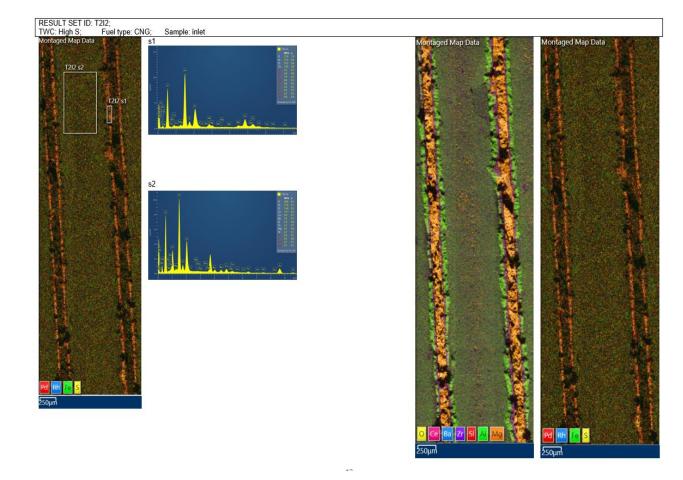




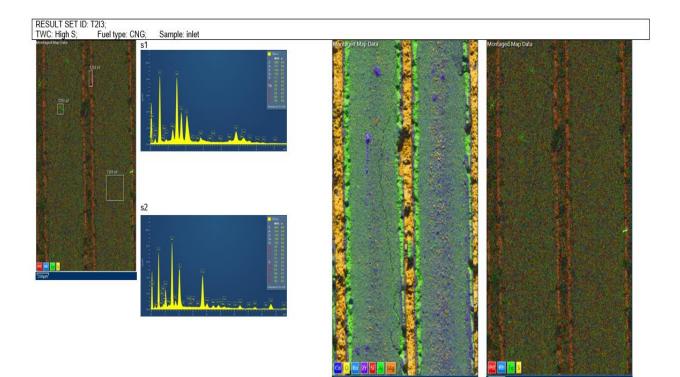




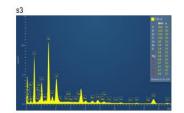






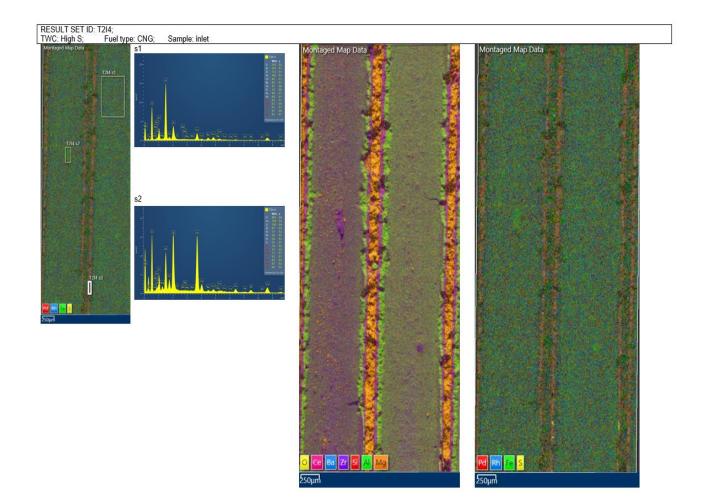




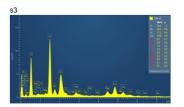




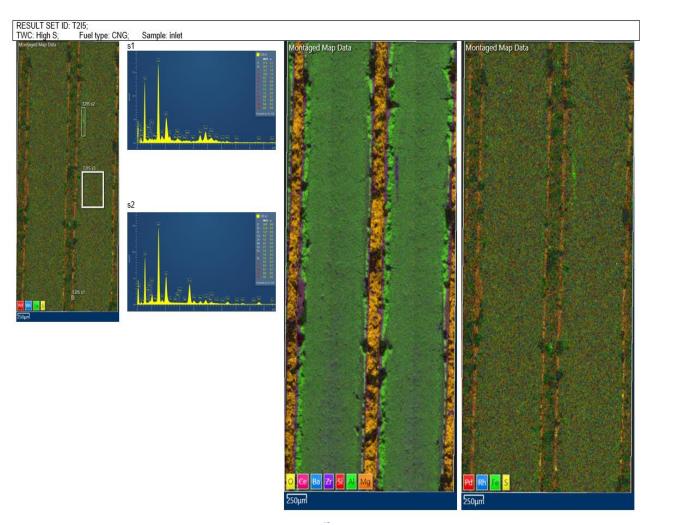




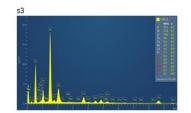






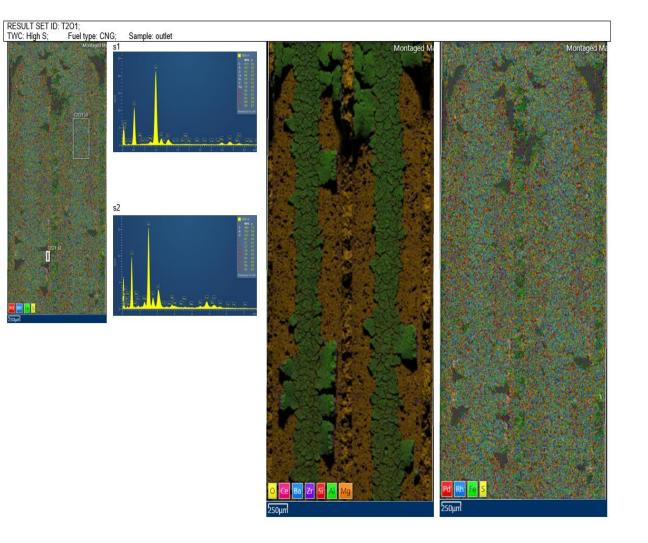






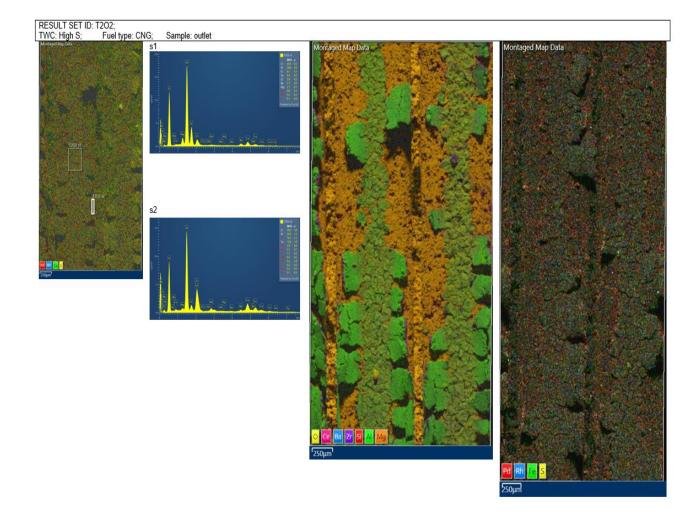


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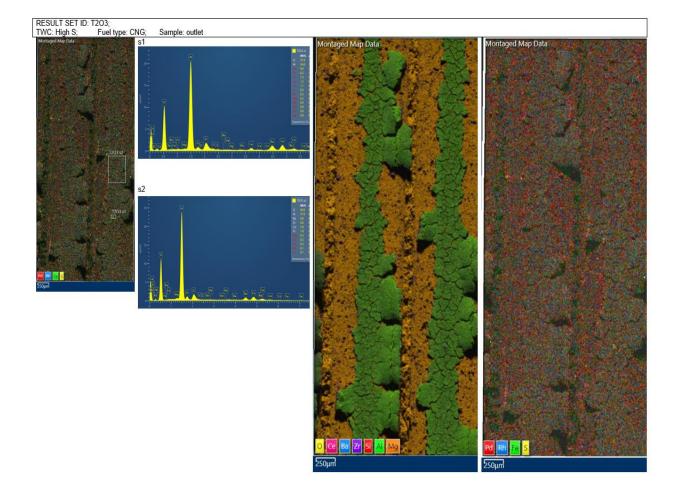




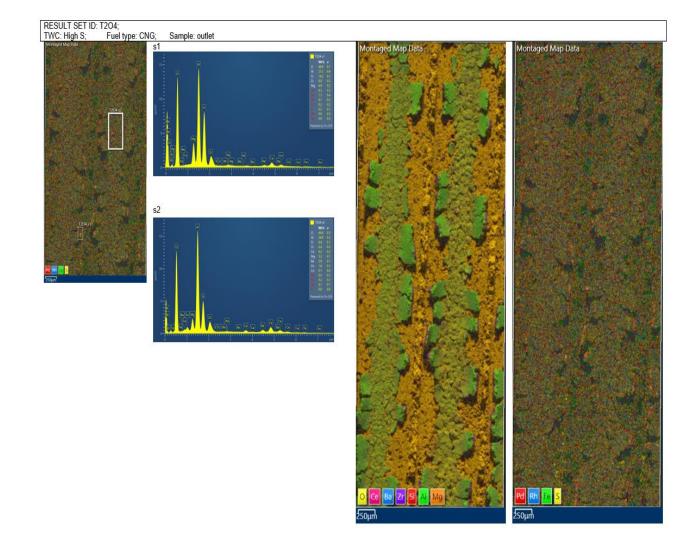




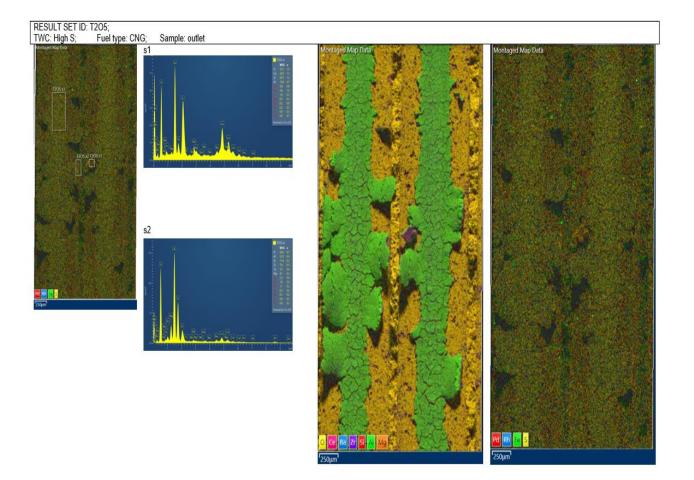




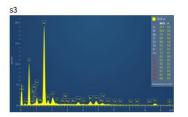








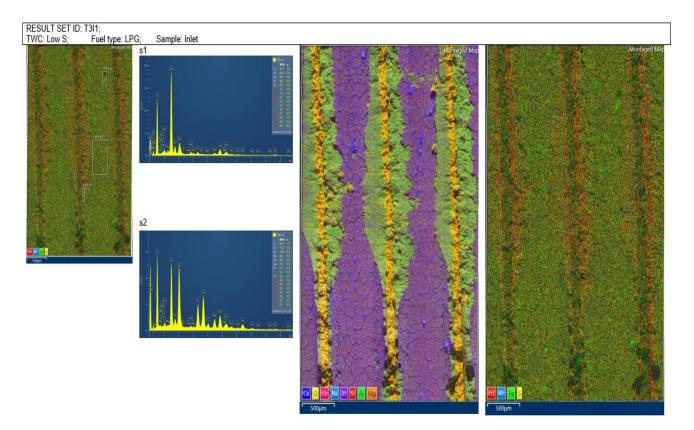




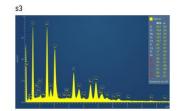


Annex 2

SEM result sets for LPG test objects (TWCs 3 and 4)

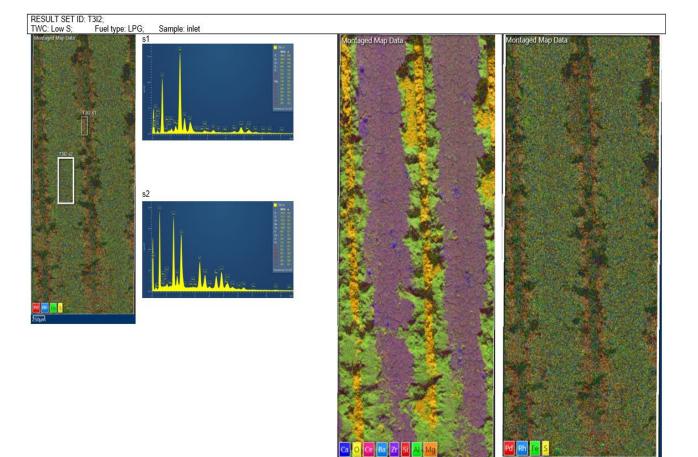






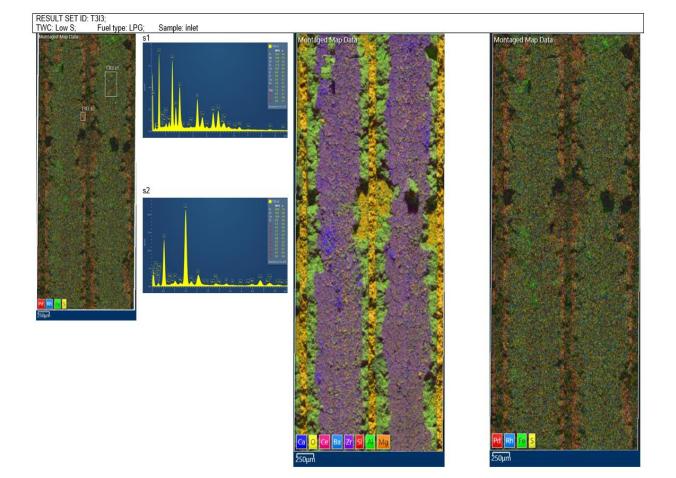




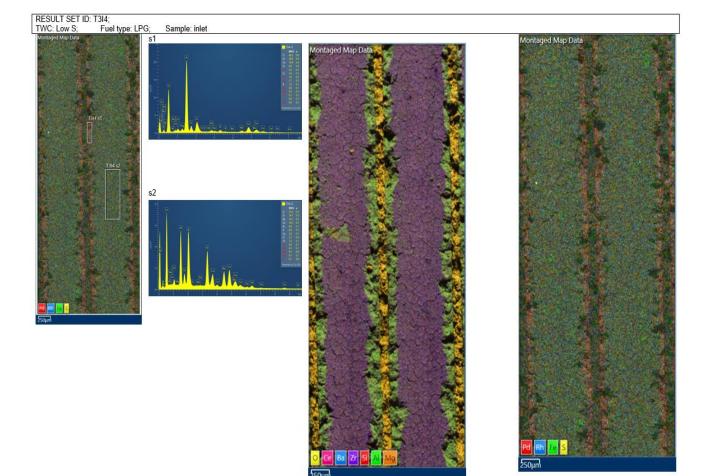


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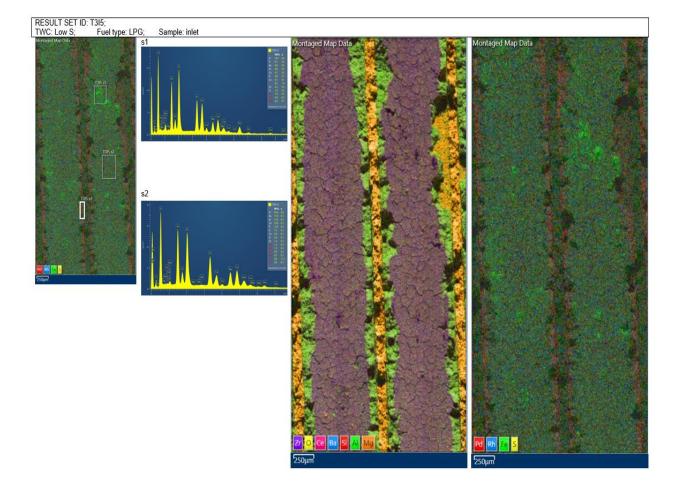




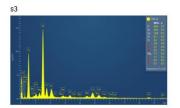






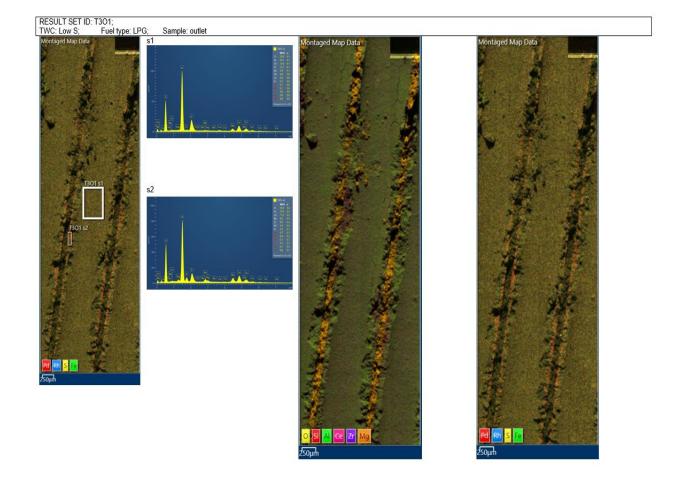




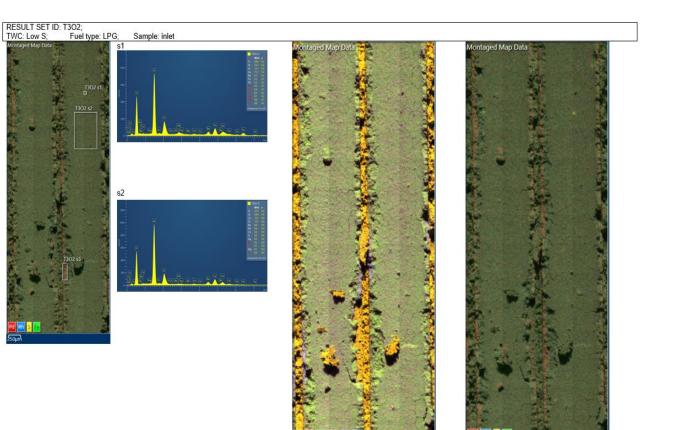








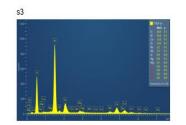




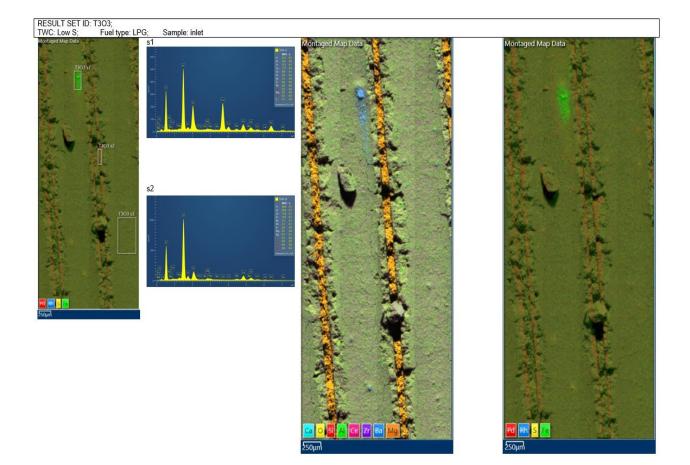
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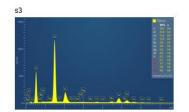






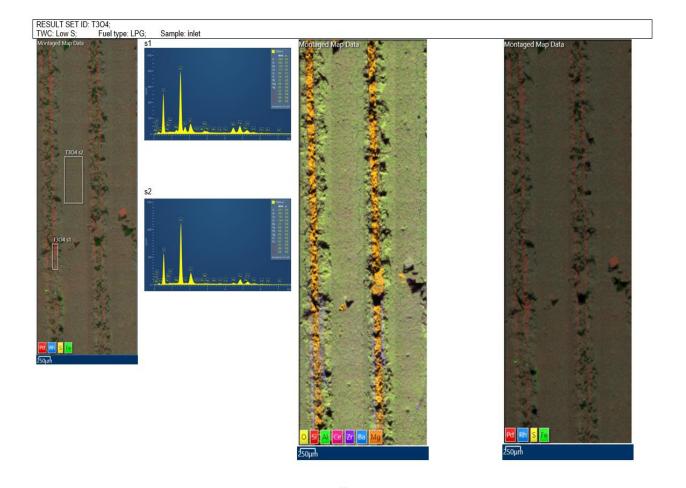




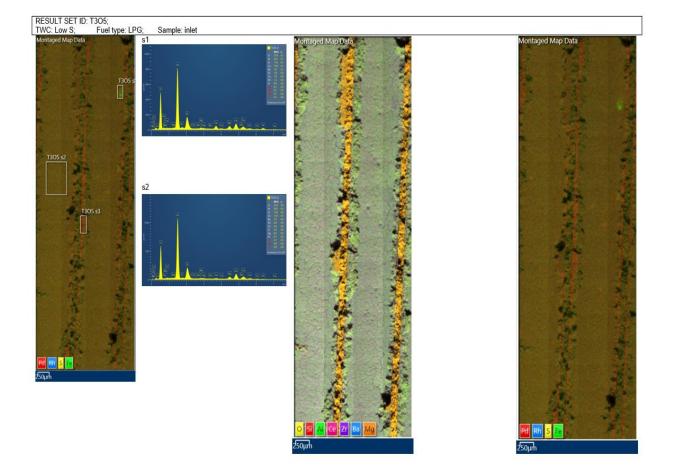




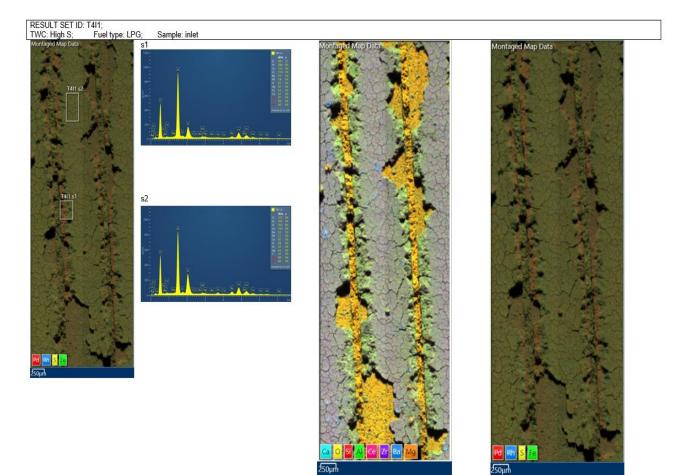




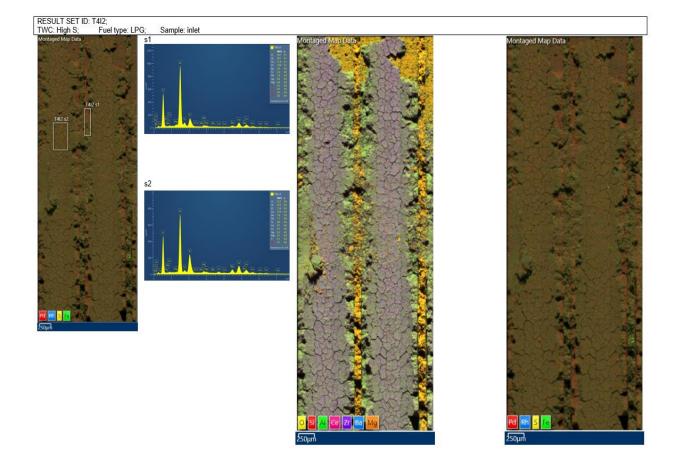






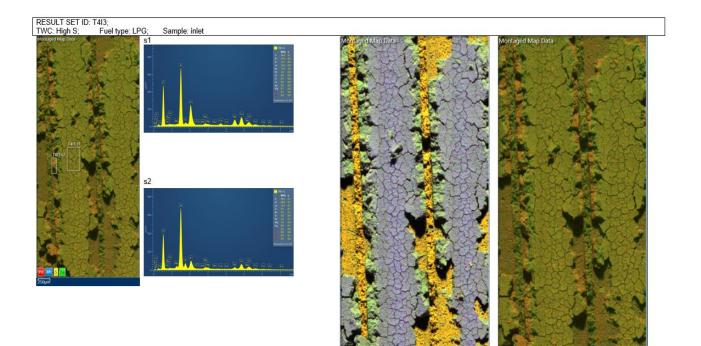






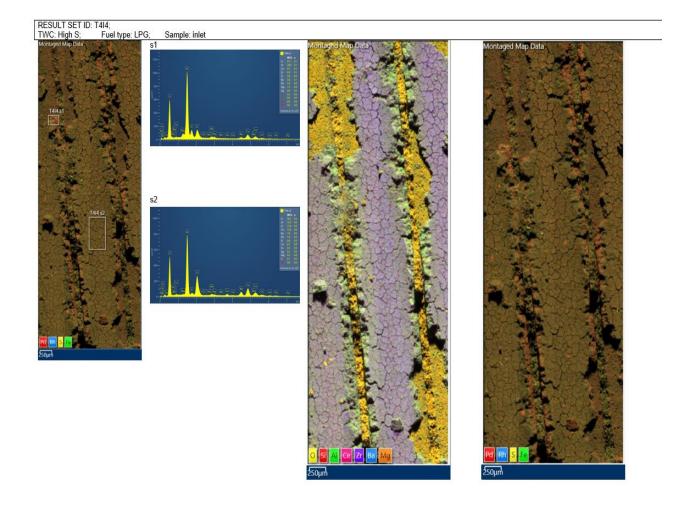
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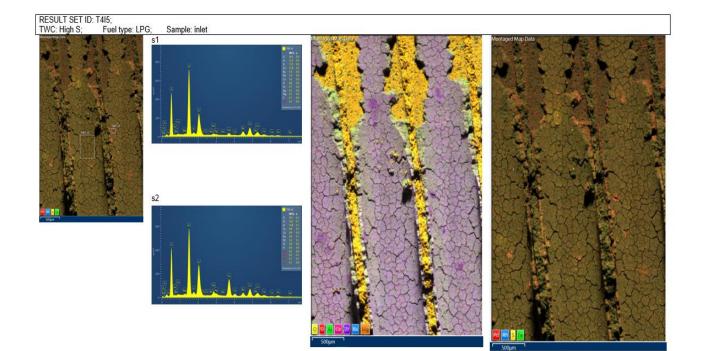






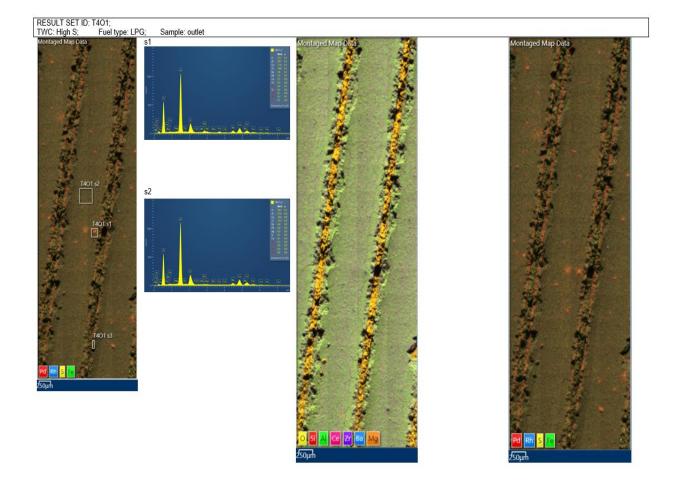




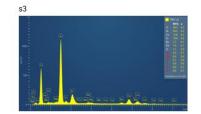






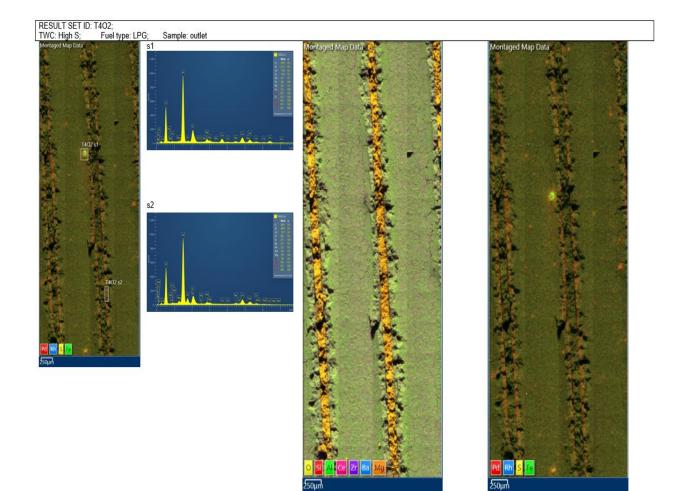




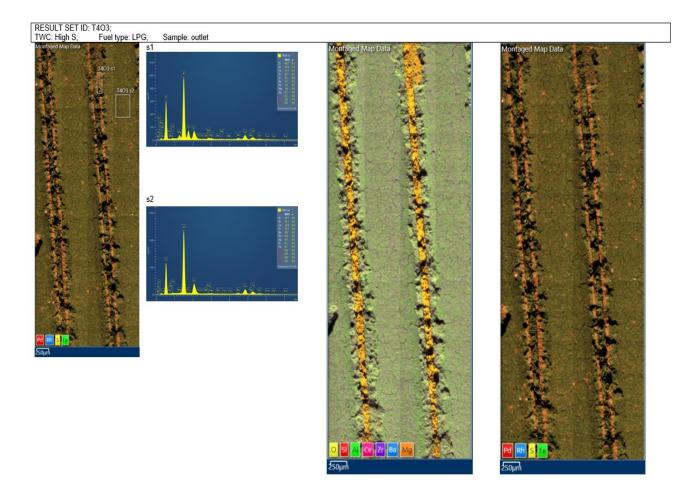




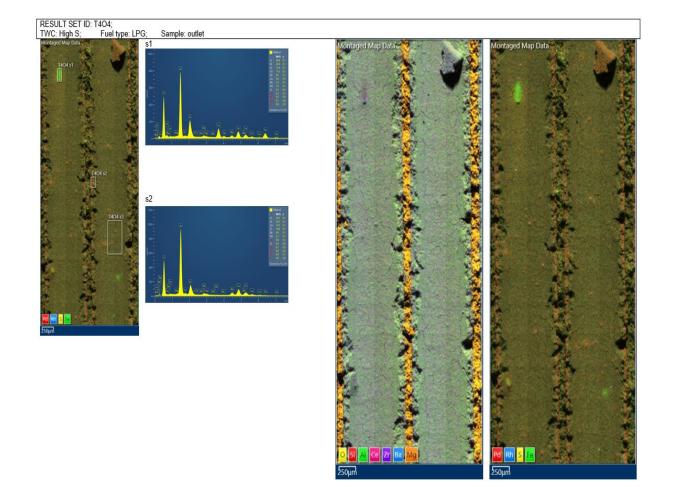




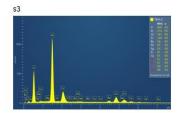




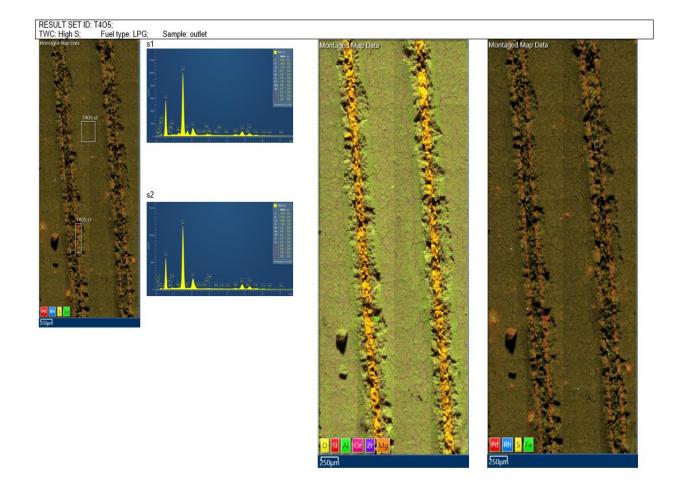












Concawe Boulevard du Souverain 165 B-1160 Brussels Belgium

Tel: +32-2-566 91 60 Fax: +32-2-566 91 81 e-mail: info@concawe.org http://www.concawe.eu

