European Commission

JRC SCIENCE FOR POLICY REPORT

Durability demonstration programme for Euro 6 passenger cars: thermal load to after-treatment systems

Final report

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2018

EUR 29278 EN

Joint Research Centre

JRC Science Hub
https://ec.europa.eu/jrc

JRC108759

EUR 29278 EN

PDF ISBN 978-92-79-88014-8 ISSN 1831-9424 doi:10.2760/510305

Luxembourg: Publications Office of the European Union, 2018

How to cite this report: Zardini A., Giechaskiel B., Martini G., *Durability demonstration programme for EURO 6 passenger cars: thermal load to after-treatment systems: Final report*, EUR 29278 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-88014-8, doi:10.2760/510305, JRC108759

Durability demonstration programme for EURO6 passenger cars: thermal load to after-treatment systems: Final report
The thermal aging of emission control devices is the most important cause of vehicles' emissions deterioration. This report compares the thermal load generated by the Standard Road Cycle (SRC) with that generated by the Worldwide-harmonized Light-duty Test Cycle (WLTC) on 2 gasoline and 2 diesel vehicles, confirming that the SRC is fit for the purpose.

Contents

Acknowledgements

The authors would like to acknowledge the technical staff of the Vehicles Emissions Laboratories (VELA) of the European Commission's Joint Research Centre, and in particular:

Dominique Lesueur, Philippe Le Lijour, Mauro Cadario and Alessandro Zappia.

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Executive summary

Policy context

The Sustainable Transport Unit (STU) of the Directorate for Energy, Transport and Climate at the European Commission − Joint Research Centre (JRC) supports the activity of the UNECE World Forum for Harmonization of Vehicle Regulations (WP.29) and in particular the development of the Worldwide harmonized Light vehicles Test Procedure (WLTP). This study will provide inputs to the Durability Task Force of the WLTP working group. This task is included in an Administrative Arrangement between JRC and Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Automotive and Mobility Industries (DG-GROW).

In order to improve the air quality and the energy efficiency of road vehicles, the European Union (EU) has regulated the exhaust emissions of vehicles with internal combustion engines since 1970 and introduced in 1986 the first Euro 1 set of standards for passenger cars ([1]). At present, the reference standard for passenger cars is the Euro 6 ([2]), featuring among other things:

- More stringent emission limits for the gaseous pollutants (hydrocarbons, carbon monoxide and nitrogen oxides) compared to previous EURO standards;
- Particulate pollutants both in terms of mass and number for diesel and direct injection gasoline vehicles.

In addition, new provisions for Real-driving Emission testing in order to better reflect emissions produced on the road are applicable as described in Regulation (EU) 2017/1151 ([3]), and Regulation (EU) 2017/1154 ([4]).

In particular with the Euro 5/6 implementation, vehicles have been subject to stricter durability requirements, i.e. they shall comply with emission limits for a minimum period of service known as "useful life" equivalent to 160 000 km for Euro 5/6 passenger cars (80 000 km for Euro 4 and previous steps). The Type V test described in the UNECE light duty emission regulation for type approval ([5]) has the objective of demonstrating that the candidate vehicle complies with the durability requirements. This test is designed to show that the deterioration of the exhaust emissions due to the ageing of the engine and related anti-pollution systems (typically, catalysts, filters and sensors) is kept under control during the vehicles' useful life. Currently, the Type V test allows the use of different test procedures to determine the deterioration factors to be used at the emission type approval testing:

- Full mileage accumulation via the Standard Road Cycle (SRC) or the Approved Mileage Accumulation cycle (AMA);
- Accelerated ageing procedures on engine test benches via the Standard Bench Cycle and Standard Diesel Bench Cycle;

In the case of gasoline cars, assigned Deterioration Factors

The SRC, developed by US-EPA ([6]) and introduced as such in the Euro 5/6 Regulations, should result in a predicted emission deterioration equal to, or more severe than the deterioration rates experienced by a significant majority of in-use vehicles. The SRC appropriateness for EU (and in general non-US) test procedures and vehicles and in particular its severity (in terms of thermal load)), which had never been assessed before, has been evaluated in this study by comparing it to the Worldwide harmonized

([1]) Directive 70/220/EEC, Official Journal, L76.
([2]) Regulation (EC) No 715/2007, Official Journal L171, and related implementing regulations.
([3]) Regulation (EU) 2017/1151, Official Journal *L 175, 7.7.2017, p. 1–643*
([4]) Regulation (EU) 2017/1154, Official Journal *L 175, 7.7.2017, p. 708–732*
([5]) Regulation No 83 of the Economic Commission for Europe of the United Nations, Official Journal L172, 2015.
([6]) EPA, 40 CFR Part 86, Federal Register Vol. 71, No. 10, 2006.

Light-duty Test Cycle (WLTC) which was designed from average driving patterns. The WLTC is presently used in EU to assess the exhaust emissions test at type-approval, for the conformity of production, and for the intermediate steps of the durability procedure.

Scope of the Report and Main findings

Box 1. Scope of the Report.

Task 1. Experimental activity (roller bench tests) on a series of Euro 6 passenger cars in order to compare the thermal load experienced by the pollution control devices during the SRC driving cycle versus the WLTC driving cycle.

Task 2 Literature survey on the deterioration of pollution control devices of diesel vehicles.

Main findings for Task 1

After testing 4 passenger cars (2 with gasoline engines and 2 with diesel engines) over several repetitions of the WLTC and SRC driving cycles we can conclude that:

— The thermal load related to SRC tests was statistically similar to that of WLTC for the 2 gasoline vehicles

— For the 2 diesel vehicles the thermal load related to SRC tests was from 1.5 to about 4 times larger than that of WLTC, depending on the chosen sampled variable (pre-cat or post-cat temperatures) and input parameters (reference temperature and thermal reactivity of the anti-pollution systems).

— Repetitions of SRC tests can exhibit a large dispersion of thermal load results (as measured from the exhaust gas temperature variations) even in the case of identical speed traces (within the allowed speed tolerance) and this is mainly due to the different driving styles and gear-shift strategies applied arbitrarily by the driver in absence of specific legislation provisions.

— The SRC test to be performed in type-approval Test V will benefit in terms of repeatability from the introduction of an agreed gear-shift strategy and driving instructions

— WLTC and SRC tests during which the regeneration of the diesel particle filter occurred were characterized by dramatically larger thermal loads than in tests without diesel particle filter regeneration.

— The regeneration frequency of the diesel particle filter may be considerably different for different passenger car models. We found a mileage between 2 DPF regenerations equal to about 200 km for vehicle 3 and about 900 km for vehicle 4 meaning that vehicle 3 and vehicle 4 would experience about 800 and 180 regenerations, respectively, during their useful life (160 000 km).

— The analysis of the contribution to total thermal load from WLTC test without DPF regeneration and from tests when the regeneration occurred indicated that during the useful life of the vehicle 25% of the thermal load is related to mileage driven in between 2 regeneration events.

Given the results above, we can conclude that the SRC test is appropriate for the durability type-approval Test type V.

Quick guide

The term **durability** refers to the ability of a device to perform some required action over a period of service. Passenger cars naturally age with use and so do their engines and pollution control devices such as catalytic converters, adopted to reduce gaseous pollution (unburned hydrocarbons, carbon monoxide, nitrogen oxides), and particle filters.

According to the European emission legislation, car manufacturers shall demonstrate that their pollution control devices are durable, i.e. that the exhaust emissions remain below a prescribed emission limit at least during the vehicle's useful life (set at 160 000 km for Euro 6 vehicles).

This is typically achieved by demonstrating that the emissions at the type approval are lower than the emission standard by a given multiplicative factor that takes into account the deterioration of the efficiency of the pollution control devices.

Actual emission deterioration factors of passenger cars are measured by using aging procedures that can be split into whole vehicle tests (on a track or on a roller bench with a chassis dynamometer) or engine bench tests. This Report deals with roller bench tests.

Specific driving cycles have been designed in order to accumulate vehicle's mileage on a roller bench or on a track, such as the Approved Mileage Accumulation (AMA) and the Standard Road Cycle (SRC) cycles, which are different from test cycles introduced for exhaust emission monitoring, like the Worldwide harmonized Light-duty Test Cycle (WLTC).

Furthermore the WLTC has been developed much more recently compared to the AMA and the SRC aging cycles.

Specific aim of this Report is the comparison of the thermal load on anti-pollution systems when driving the vehicle over the WLTC versus SRC, in order to validate the durability test procedure.

1 Introduction

1.1 Rationale

Air quality in the European Union (EU) is remarkably affected by the pollutants emitted by internal combustion engines, such as those powering road vehicles (EEA, 2017). Light-duty vehicles (passenger cars) in the EU market have been subject since 1970 to a type approval procedure which includes a demonstration of compliance of exhaust emissions with limit values set by the relevant emission legislation, which at present is the Euro 6 package (Regulation (EC) 715/2007 and Regulation (EU) 2017/1151). Monitored pollutants include total hydrocarbons (THC), carbon monoxide (CO), nitrogen oxides (NOx), particulate mass and particle number. In recent years, increasingly stringent limit values required anti-pollution systems (APS) to reduce emissions at engine-out or at the tailpipe such as catalysts, filters, NOx traps, or exhaust recirculating systems (EGR). Engines and their associated APS are subject to deterioration with use, resulting in increased exhaust emissions with vehicle's age. This is why, besides Type I tests, manufacturers shall demonstrate via prescribed durability test procedures (Type V test) that vehicles' emissions remain below the limit values for a period of service-time measured in km referred to as **useful life**, which is set to 160 000 km for Euro 6 passenger cars. The comparison of emission values at the beginning and end of the durability procedure provide a deterioration factor for each pollutant, to be applied at the vehicle type approval.

Ideally for the **durability** demonstration, the emissions of a vehicle should be monitored with Type I tests at regular intervals covering the entire useful life (full mileage accumulation). According to the legislation, the full mileage accumulation can be carried out by driving the candidate vehicle on a test track or on a roller bench following a specific driving cycle. However, this is a time- and resource-consuming activity. Moreover, the driving conditions of the mileage accumulation have to be well defined in order to get reproducible and comparable results. In order to reduce the testing burden and costs, assigned deterioration factors and accelerated engine bench tests were introduced as alternative options in Regulation No 83 (and Regulation EC 692/2008).

The assigned deterioration factors are based on assessment of typical deterioration rates of pollution control devices and can be used by the manufacturers at the type approval without performing the Type V durability test. At EU level, however, a set of assigned deterioration factors was available only up to the Euro 5 step, while no deterioration factor was yet developed for Euro 6. At United Nations level, deterioration factors were introduced only for Euro 6 positive ignition vehicles. In the absence of assigned deterioration factors for compression ignition vehicles, manufacturers shall use the whole vehicle or bench ageing durability test procedures to establish deterioration factors.

The existing durability test procedures with the whole vehicle on a roller bench or track are based on two mileage accumulation driving cycles:

- The **SRC** (Standard Road Cycle);
- The AMA (Approved Mileage Accumulation) cycle.

As described in the United States Environmental Protection Agency (US-EPA) final rule that first introduced the SRC for passenger cars (EPA, 2006), the durability demonstration process should be designed not to reflect realistic ageing conditions but to predict expected in-use deterioration rates and emission levels that represent a significant majority (approximately 90%) of the distribution of emission levels and deterioration in actual use. The Approved Mileage Accumulation (AMA) cycle was developed before vehicles were equipped with catalytic converters and it is focused mainly on low speed driving responsible for deposit formation, the main emission deterioration mechanism in engines without after-treatment devices. For this reason, the AMA cycle is considered obsolete and will not be part of the present study.

The US-EPA durability demonstration procedure and the SRC are based on the following assumptions:

— Engine out emissions are relatively stable over the useful life of the vehicles;

— The thermal aging represents the most important aging mechanism.

While the first assumption can be considered generally true for gasoline powered vehicles, the stability of engine out emissions of diesel engines is a question mark when emission control technologies affect the combustion process (e.g. Exhaust Gas Recirculation, EGR). The second assumption is acceptable for a conventional three way catalyst which is the main pollution control device used in vehicles typical of the US market. However this assumption cannot be extended to other pollution control devices like filters and NOx abatement systems for which deposits and chemical poisoning may represent a more important ageing mechanism.

As a result of a global harmonization effort, a new test procedure for light duty vehicles (WLTP) is being developed in the context of the UNECE WP29 working group. So far, only the Type I test has been fully developed in the context of the WLTP while other tests have still to be discussed or finalized. As far as the Type V test is concerned, considering the Regulation 83 as starting point, a first point to be evaluated is to what extent the SRC can be used as mileage accumulation cycle in a globally harmonized test procedure.

Given that

1. The SRC is a mileage accumulation cycle for the durability demonstration based on the 90th percentile (for the US vehicle market) of the distribution of emission levels and deterioration in actual use, and that
2. The Type I Test is based on average driving conditions derived form a large activity database which are reflected in the WLTC driving cycle,

the question arises how the SRC compares to WLTC in terms of engine load and thus of thermal load the pollution control devices are exposed to. The investigation of exhaust emissions deterioration rates from a statistically significant number of instrumented in-use vehicles during their useful life would not be a realistic solution. The followed approach is therefore the comparison of WLTC and SRC thermal loads. The SRC cycle should in principle expose the APS to a thermal load (TL) similar to or larger than that from the WLTC. The extreme cases in which

— SRC_{TL} >> $WLTC_{TL}$, or

— SRC_{TL} << $WLTC_{TL}$

might represent an issue. In the former case, the SRC might result in excessive and unrealistic thermal load compared to WLTC. In the latter case, the SRC would result a too mild ageing cycle compared to the WLTC that would better represent the expected deterioration mechanisms, besides the averaging driving patterns, and the SRC would become unnecessary. This is the core topic of the experimental activity reported in the present work.

At present, the UNECE Regulation No. 83 assumes that:

— Gasoline after-treatment systems (ATS) deteriorate mainly by thermal ageing, while diesel ATS deteriorate due to the extreme heat events during diesel particle filter (DPF) regenerations (to comply with the Euro 5 standards, particulate filters and the oxidation catalysts were the only technologies considered necessary).

— Manufacturers can choose to use assigned deterioration factors for gasoline vehicles, while deterioration factors for diesel vehicles have not been assigned yet.

— To take into account that during an accelerated aging test the after-treatment device is exposed to a smaller amount of chemical agents (ashes from lubricant and fuel mainly) that in a full mileage accumulation, the reduced chemical poisoning effect is compensated by an additional 10% thermal aging (multiplicative 1.1 factor to the thermal load). However, the impact of chemical poisoning on the most recent technologies such as de-NOx and selective catalyst reduction (SCR) systems, and gasoline particle filters has not been fully assessed. In addition, in diesel and gasoline particulate filters (DPF and GPF) the accumulation of ash mainly coming from the lubricant may represent an issue to be taken into consideration.

— The New European Driving Cycle (NEDC) is the emission test of choice used to calculate the deterioration factors during the durability procedure, while UNECE Global Technical Regulation (GTR) No. 15 ([7]) and the EU legislation have already introduced the newer WLTC since 2017.

1.2 The Durability Task Force (DTF)

In order to simplify the type-approval legislation in line with the recommendations contained in the final report of the CARS 21 High Level Group ([8]), at European level it was decided to repeal several Directives by replacing these, where appropriate, with references to the corresponding UNECE Regulations, as incorporated into Community law in accordance with Decision 97/836/EC ([9]). Consequently, UNECE Regulations should be incorporated within the Community type-approval procedure either as requirements for the European Commission (EC) vehicle type-approval, or as alternatives to existing Community law. The European Commission disposes of a mandate in order to negotiate new UN Regulations and UN GTRs in the name of all 28 Member States.

In this context the Durability Task force was established in October 2016 in the framework of the United Nations worldwide-harmonized light duty test procedure (WLTP) informal working group (IWG) which received the mandate to develop durability requirements for conventional and electrified vehicles as regards to pollutant emissions. The work of the DTF should consist of revising the current procedure laid down in UNECE Regulation No. 83, which is based on mileage accumulation following the Approved Mileage Accumulation durability cycle (AMA) or, alternatively, the Standard Road Cycle (SRC).

Objective of the DTF

"Define a procedure for assessing the evolution of pollutant emissions during the lifetime of the vehicle"

Mandate of the DTF

The DTF shall:

— Be open to all experts and stakeholders that have an interest in WLTP;

— Be chaired by the European Commission;

— Develop a procedure to demonstrate the durability of pollutant control devices for the WLTP GTR;

— Act as a platform for the exchange of information and contributions of stakeholders, to be discussed and agreed during the development process;

— Report to the WLTP-IWG on the progress;

— Deliver technical advice and a GTR text proposal;

— Focus only on the technical issues regarding the procedure to be developed, while political decisions are made at the WLTP level.

Work plan

The DTF agreed on the following work plan:

([7]) Global technical regulation No. 15, Worldwide harmonized Light vehicles Test Procedure. Available at: https://www.unece.org
([8]) Available at: http://ec.europa.eu/growth/content/cars-21-high-level-group-final-report-2012-0_en
([9]) Official Journal, L 346, 17.12.1997, p. 78–94.

— Action 1. Experimental measurement campaign to compare the thermal load to after-treatment devices of passenger cars driven over different driving cycles (SRC and WLTC);

— Action 2. Literature survey on gasoline vehicle after-treatment systems;

— Action 3. Literature survey on diesel vehicle after-treatment systems and EGR.

1.3 Specific JRC tasks

The Sustainable Transport Unit of the JRC has an Administrative Arrangement (AA N. 34263) with the Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Automotive and Mobility Industries of the European Commission (DG-GROW) to provide support on a number of technical elements related to the emission legislation. Among the various tasks there is the following one:

Task 2(of the AA N. 34263). Support to the standardization activities of vehicle emissions within UNECE

Sub-task 2.1: WLTP IWG

Phase 1 of the WLTP programme has been completed in 2016. During the January 2016 meeting of the Working Party on Pollution and Energy (GRPE) Phase 2 has been launched and it will remain active from 2016 until 2020. JRC will still be involved in various task forces/activities being the most relevant listed below:

— Driving Cycle Task Force
    - o Normalization of Test results
    - o Driving Indexes

— Supplemental Test Task Force
    - o Low Temperature tests
    - o MAC
    - o Eco-Innovations

— Evaporative Emissions Task Force

— In-Service Task Force
    - o Emissions, CO_2, Road Load

— EV/HEV and collaboration with EVE IWG

— Additional Pollutant Task Force: follow up of phase 1B

In agreement with DG-GROW, the JRC was also involved in the Durability Task Force of the United Nations WLTP, chaired by DG-GROW itself. In this context the JRC was asked to contribute to part of Action 1 (experimental measurement campaign) and the coordination of Action 3 (literature survey); see below. The activity of the JRC in the WLTP task forces in general entails the participation in the relevant meeting, scientific and technical support to the discussion, conducting experimental programmes whenever this is needed, contributing to drafting technical documents. The specific activity in each task force will depend on how the work will evolve, on the priorities and the needs agreed with DG-GROW. The outcome of the above described task will be part of the following deliverable:

Deliverable 2.1: Technical input for the WLTP sub-working groups.

<u>**Task 1** (of the present Report, corresponding to Action 1 of the DTF work plan)</u>

The JRC should use its Vehicles Emissions Laboratories (VELA) to perform whole-vehicle roller bench tests on a limited number of passenger cars to compare the thermal load to the after-treatment systems during the SRC versus WLTC driving cycles.

Task 2 (of the present Report, corresponding to Action 3 of the DTF work plan)

The JRC should collect information (books, articles, presentations, etc.) on:

- Aging mechanisms causing deterioration of (existing and under development) ATS and their relative importance (e.g. thermal aging vs chemical poisoning vs mechanical stress)
- Methods used to simulated these deterioration effects in accelerated bench aging tests (e.g. chemical poisoning)
- Characteristics of the engine to be used for accelerated bench aging if not the same for which the ATS had been designed.
- The impact of exhaust flow rate on accelerated bench aging tests
- Different EGR systems and their interaction with engine durability issues
- Impact of different EGR rates on its durability and engine drivability

2 Task1: Experimental campaign to compare WLTC and SRC thermal loads

2.1 Facility and vehicles

Experiments were carried out at the Vehicle Emissions Laboratory of the European Commission – Joint Research Centre (Italy), equipped with a dynamometer test cell; see Figure 1. Four Euro 6 passenger cars available on the European market, 2 with compressed-ignition (CI) and 2 with spark-ignition (SI) engines, were chosen for the test programme; see technical details in Table 1. The cars were rented from generic rental companies without the involvement of the vehicle manufacturers. The vehicles were run on a roller bench following the prescribed speed traces of the Worldwide-harmonized Light-duty Cycle (WLTC) and the Standard Road cycle (SRC) displayed in Figure 2 (see also section 1.1). The vehicles were instrumented with thermocouples in the exhaust pipe for pre-catalyst (pre-cat) and post-catalyst (post-cat) temperature acquisition. In addition, the raw exhaust gas was sampled via a heated line (190 °C) and analysed in terms of total hydrocarbons (THC), carbon monoxide and dioxide (CO, CO_2) and nitrogen oxides (NOx).

During the tests, several parameters were acquired at 10 Hz sampling rate and averaged at 1 Hz; see Figure 3 and Figure 4:

- Raw exhaust concentrations of gaseous components (AMA i60, AVL):
  - Flame ionization detector for THC and methane (CH_4);
  - Chemi-luminescence detector for NOx;
  - Non-dispersive infrared for CO and CO_2.
- Diluted and thermally treated exhaust concentration of particles (at 1 Hz) with condensation particle counters compliant with UNECE Regulation No. 83.
- Temperatures (thermocouples):
  - Engine oil,
  - Pre-catalyst, i.e. the temperature before the after-treatment system of the exhaust gas, typically very close to the outlet of the combustion chamber;
  - Post-catalyst, i.e. the temperature after the after-treatment system;
  - Tailpipe exhaust temperature;
- On board diagnostic (OBD) signals when available, such as engine speed and temperatures;

The WLTC is an emission test cycle now mandatory for the type-approval Type I test of new vehicle types in EU: Verifying average exhaust emissions at ambient conditions. It replaces the old New European Driving Cycle (NEDC). The SRC is a mileage accumulation cycle used in EU-type approval Type V test: Verifying the durability of pollution control devices test. Both WLTC and SRC have been adopted by the United Nations as described respectively in Global Technical Regulation (GTR) No. 15 and UNECE Regulation No. 83, respectively.

The exhaust concentrations of pollutants were recorded for each test in order to:

- Assure the quality of test results, highlighting malfunctions (e.g. misfire) that could influence the temperature profiles;
- Support the occurrence of particle filter regeneration for diesel vehicles.

Figure 1. The Vehicles Emissions Laboratories (VELA) test cell at JRC (left) and a passenger car on the roller bench inside the test cell (right).

Source: JRC

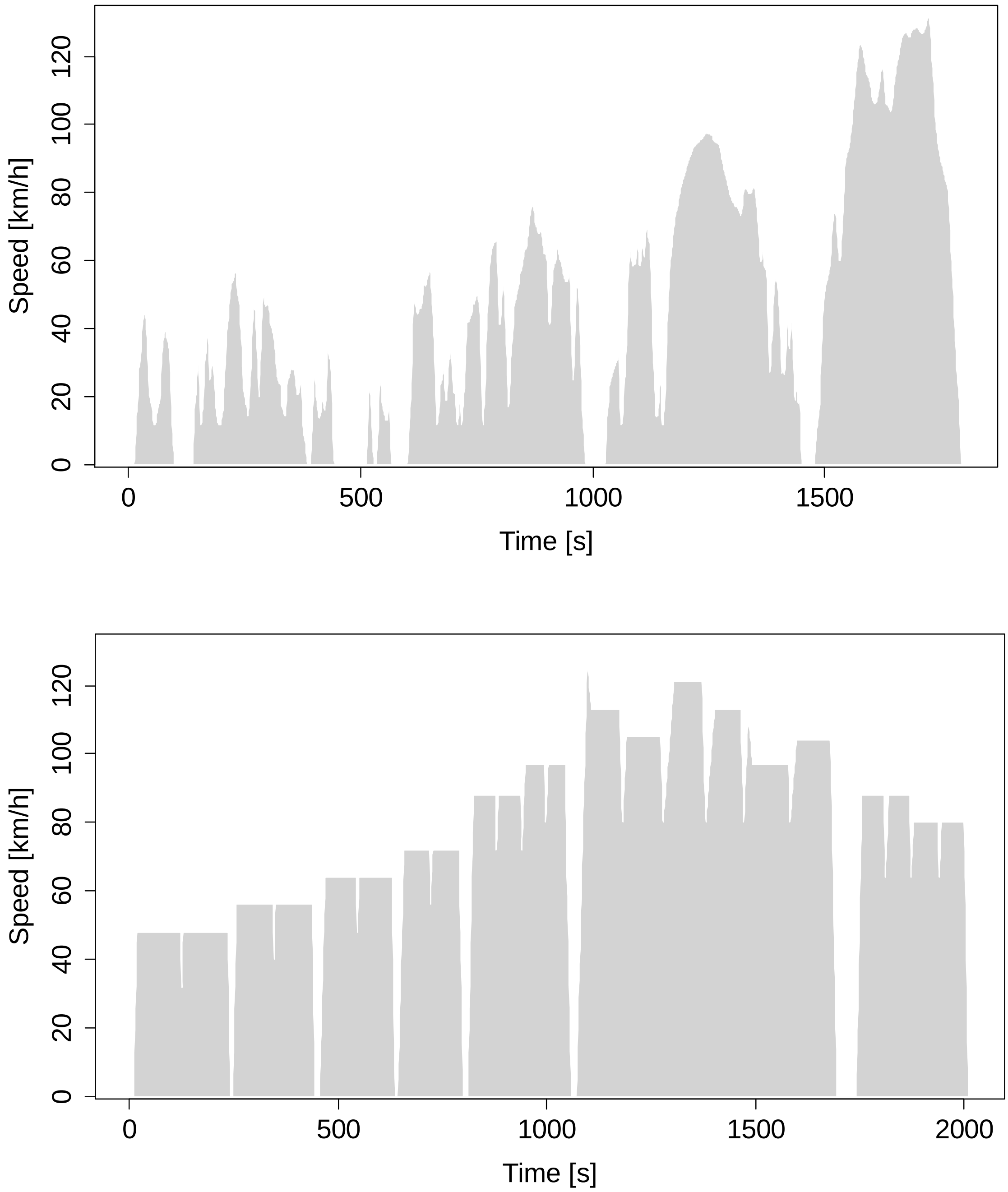
Table 1. Vehicles' technical specifications. All vehicles were homologated for the EU market and were rented from generic dealers.

Vehicle	1	2	3	4
Engine type(1)	SI	SI	CI	CI
Injection(2)	PFI	GDI-s	DI	DI
After-treatment(3)	TWC	TWC	DOC, LNT, DPF	DOC, SCR, DPF
EURO	EURO 6b	EURO 6b	EURO 6b	EURO 6b
Fuel	E10	E10	B7	B7
Displacement [cm^3]	1242	999	1461	1560
Cylinders	4	3	4	4
Power [kW]	51	77	66	73
Transmission	MT	MT	AT	MT
Gears	5	6	--	5
Mileage [km]	2500	3700	21190	2950
Mass [kg]	940	1260	1279	1309
Year of registration	2016	2017	2017	2017

(1) SI = spark-ignition; CI = compressed ignition
(2) PFI = port-fuel injection; GDI-s = stoichiometric Gasoline Direct Injection; DI = Direct Injection
(3) TWC = Three-Way Catalyst; DOC = Diesel Oxidation Catalyst; LNT = Lean NOx Trap; DPF = Diesel Particle Filter; SCR = Selective Catalytic Reduction

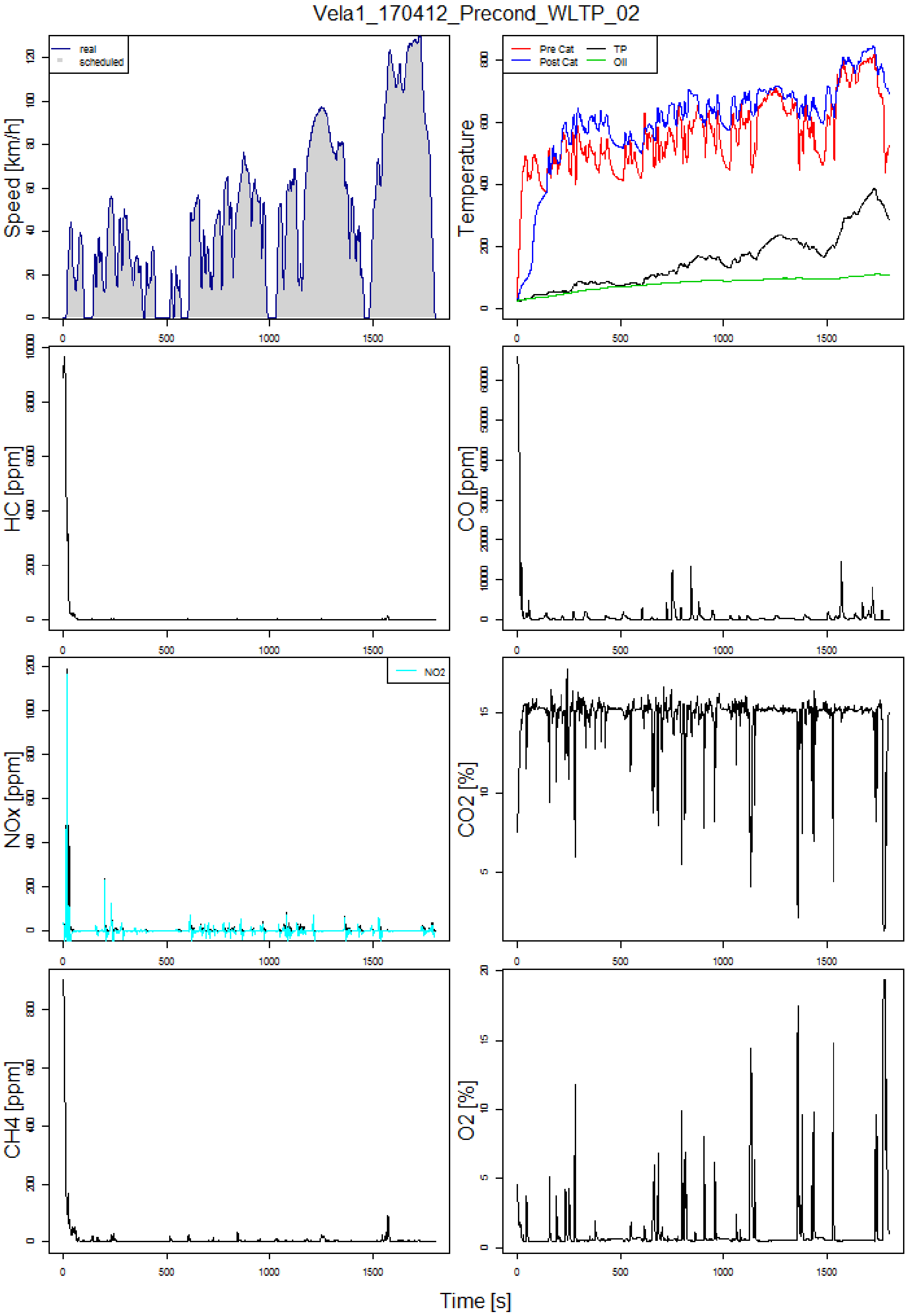
Source: Registration documents of the vehicles

Figure 2. Speed profiles of the 2 driving cycles followed by the test vehicles: WLTC (upper panel) and SRC (lower panel), see text for details.



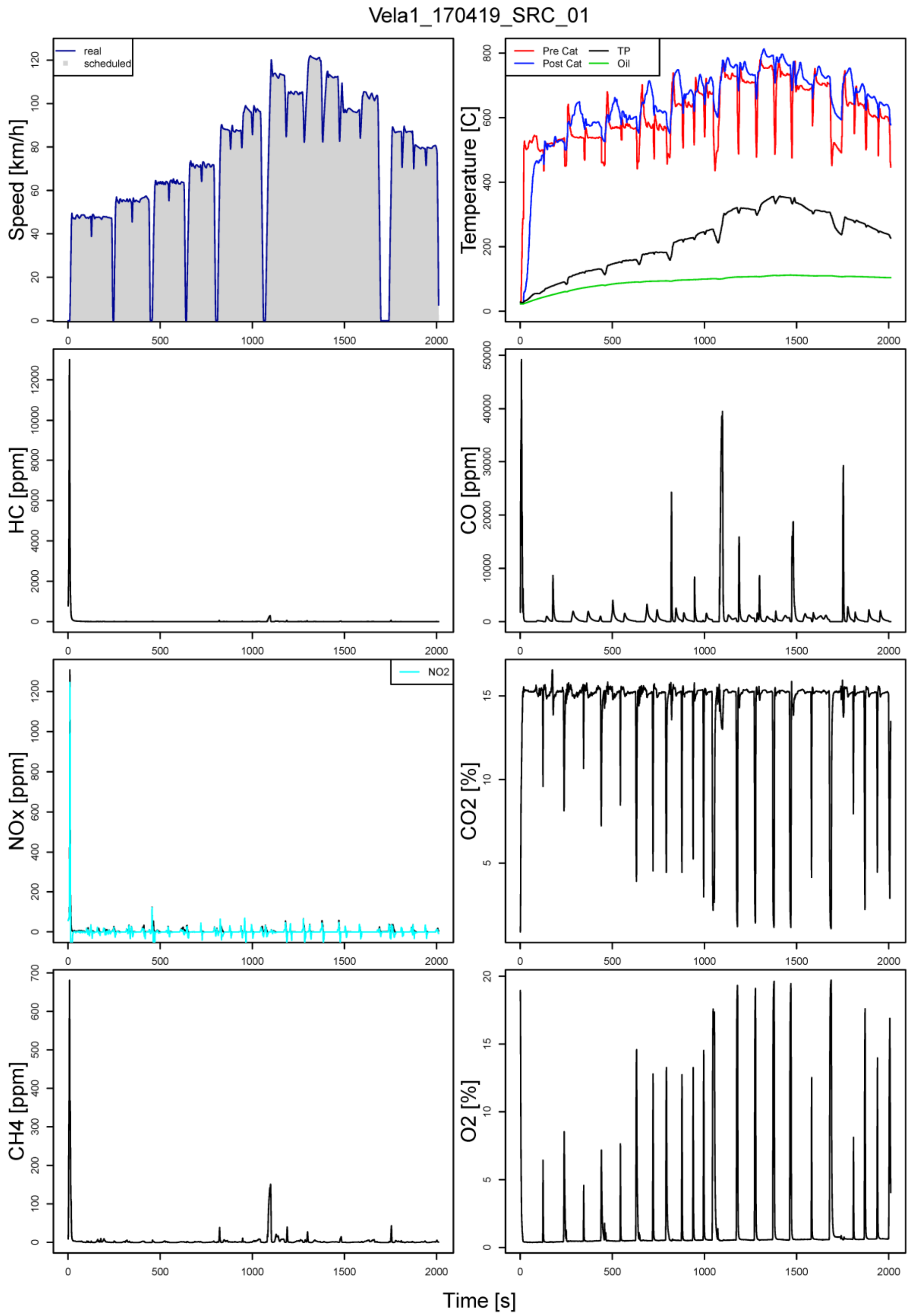
Source: JRC

Figure 3. Example of a WLTC test with temperatures from thermocouples and concentrations of the chemical component in the vehicle's exhaust.



Source: JRC

Figure 4. Example of SRC test with temperatures from thermocouples and concentrations of the chemical component in the vehicle's exhaust.



Source: JRC

2.2 Test protocol and data handling

In the following, a schematic summary of the procedures agreed prior to conduct the test programme and the method to analyze the data are presented.

2.2.1 Test protocol

Driving cycles

SRC and WLTC

Fuel

Tests shall be performed using the same fuel for SRC and WLTP (e.g., diesel B7 and petrol E10). Using always the same kind of fuels blends will avoid variations due to different calorific value of the fuels.

Preconditioning

At the vehicle arrival, prior to testing, the vehicles shall be preconditioned by performing 3x Extra-Urban Driving Cycles (EUDC, part 2 of Type I test as in Regulation UNECE No. 83) using the reference fuel. Vehicles with positive ignition engines can alternatively be preconditioned by performing 1x Urban Driving Cycles (UDC, part 1 of Type I test as in Regulation UNECE No. 83) followed by 2x EUDC.

Test sequence

— Day 1: Preconditioning

Gasoline vehicle:

— Day 2: 1 $WLTC_{cold}$ + 2 $WLTC_{hot}$

— Day 3: 1 SRC_{cold} + 1 SRC_{hot}

Diesel vehicle:

— Day 2 to day x: 1 $WLTC_{cold}$ + 2 $WLTC_{hot}$ + n $WLTC_{hot}$ (until DPF regeneration takes place)

— Day (x+1) to z (end): 1 SRC_{cold} + 1 SRC_{hot} + n SRC_{hot} (until DPF regeneration takes place)

If the regeneration takes place during 1 of the first 3 WLTC or 1 of the 2 first SRC, that test-cycle shall be repeated under the same starting conditions, i.e., cold or hot start.

An autopilot may be used for the diesel testing.

2.2.2 Data handling

Data acquisition

Temperatures in each pollution control device shall be recorded during the whole test sequence, at the location with the highest temperature, where possible. In cases where the location with the highest temperature varies over time, or where that location is difficult to define/reach, multiple bed temperatures should be recorded at suitable locations. The number and locations of the temperature measurements shall be based on best engineering judgment.

— Per each pollution control device, the temperatures shall be measured and recorded at a minimum rate of once every second (1 Hz) during the test sequence. The measured temperatures shall be tabulated into a histogram with temperature bins no larger than 10 °C; see Figure 5. In the case of multiple bed temperatures, the highest temperature each second shall be the one recorded in the histogram. Each bar of the histogram shall represent the cumulated frequency in seconds of the measured temperatures falling in the specific bin. The time in hours corresponding to each temperature bin must be determined and then extrapolated to the useful life of the vehicle (160000 km).

Calculation of the equivalent ageing time

The temperatures recorded as described above shall be reduced to an arbitrary reference temperature (T_{ref}) within the range of the temperatures recorded during the data collection phase. The value of T_{ref} for each one of the devices may vary. The equivalent ageing time corresponding to the reference temperature shall be calculated, for each bin, in accordance with the following equation (see Regulation EC 692/2008 and Regulation EU 2016/1718 for details):

$$t_e^i = t_{bin}^i \times e^{\left(\left(\frac{R}{T_{ref}}\right)-\left(\frac{R}{T_{bin}^i}\right)\right)}$$

where:

R = thermal reactivity of the pollution control device.

The following R values shall be used:

- TWC: 17 500
- Diesel oxidation catalyst (DOC): 18 050
- Catalysed DPF: 18 050
- SCR or ammonia oxidation catalyst (AMOX) based on iron-zeolite (Fe-Z): 5 175
- SCR copper-zeolite (Cu-Z): 11 550
- SCR Vanadium (V): 5 175
- LNT (lean-NOx trap): 18 050

T_{ref} = reference temperature, in degree Kelvin.

T^i_{bin} = mid-point temperature, in Kelvin, of the temperature bin *i* to which the pollution control device is exposed during the data collection phase, registered in the temperature histogram.

t^i_{bin} = the time, in hours, corresponding to the temperature T^i_{bin} adjusted to a full useful life basis.

t^i_e = the equivalent ageing time in hours needed to achieve, by exposing the pollution control device at the temperature T_{ref}, the same amount of ageing as the one that would result from exposure of the pollution control device at the temperature T^i_{bin} during the time t^i_{bin} .

i = bin number, where 1 is number for the bin with the lowest temperature

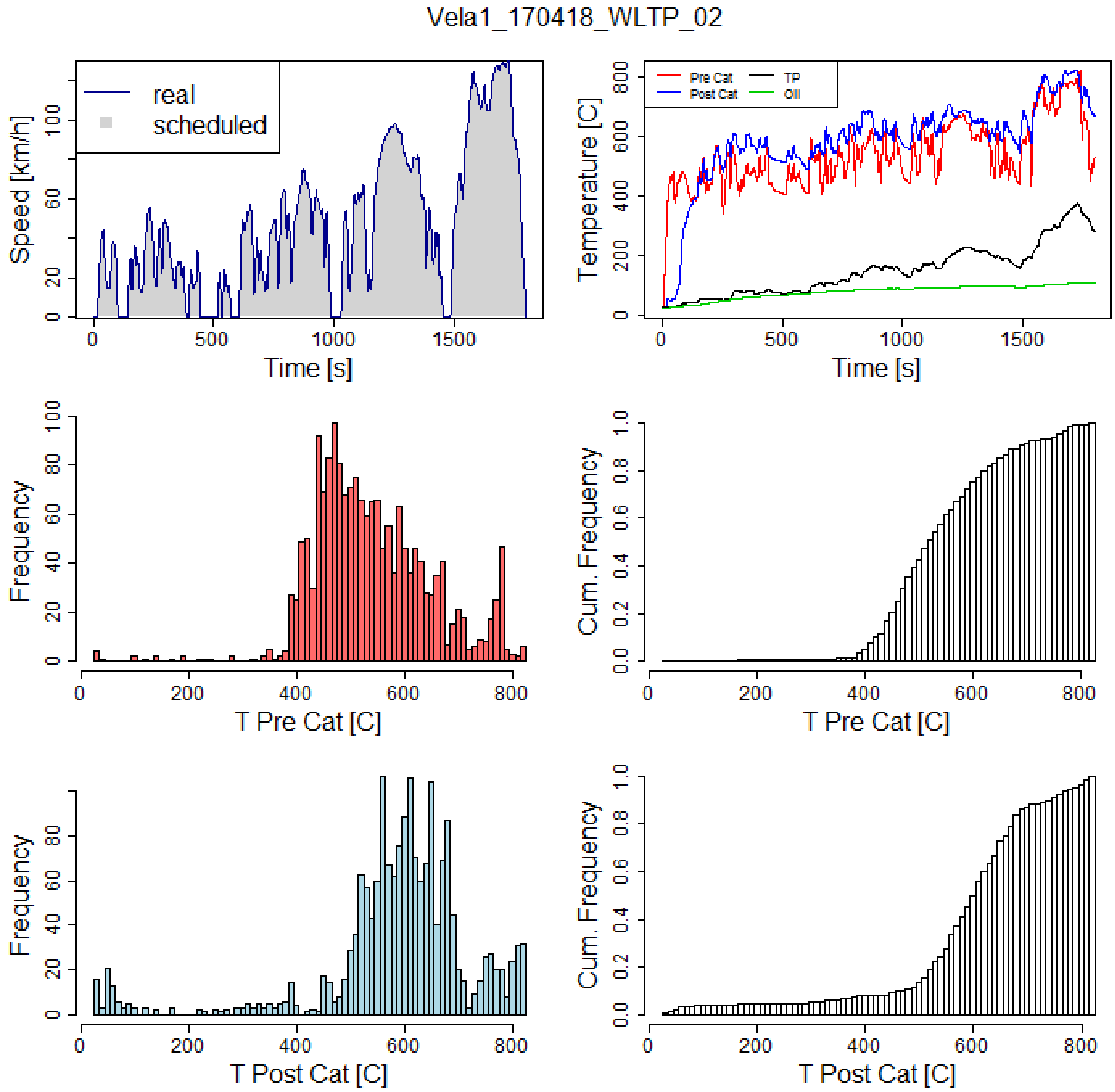
n = the *i*-value for the bin with the highest temperature.

The *total equivalent ageing time* (AT) per each pollution control device shall be calculated in accordance with the following equation:

$$\mathrm{AT} = \sum_{i=1}^{n} t_e^i$$

AT is the total equivalent ageing time, in hours, needed to achieve, by exposing the pollution control device at the temperature T_{ref}, the same amount of ageing as the one that would result from exposure of the pollution control device, over its useful life, to the temperature T^{i}_{bin} during the time t^{i}_{bin} of each one of the i bins registered in the histogram.

Figure 5. Example of data processing to obtain the equivalent ageing time from a WLTC test; speed profile in the uppermost left panel. Temperatures in the uppermost right panel were acquired at the following locations: pre-catalyst (Pre Cat), post-catalyst (Post Cat), tailpipe (TP, after the tailpipe muffler) and in the engine oil (to discriminate between cold start and hot start tests). Histograms with distributions and cumulative frequencies of pre-cat and post-cat temperatures were created for bin size = 10 degrees (middle and lowermost panels).



Source: JRC

3 Results and discussion Task 1

3.1 Vehicle 1

The technical specifications of vehicle 1, extracted from Table 1, are presented in Table 2. This gasoline port fuel injection passenger car was equipped with a close-coupled three-way catalyst for the oxidation of hydrocarbons and carbon monoxide and chemical reduction of nitrogen oxides. A first thermocouple (pre-cat) was installed at engine-out, immediately upstream of the after-treatment system (3-way catalyst); see Figure 6. A second thermocouple (post-cat) was installed under the vehicle floor and after the after-treatment system. 3x WLTC and 2x SRC cycles were run following the test matrix in Table 3 without major violations, as can be seen in Figure 7 which displays overlapped speed profiles for all tests.

The thermal reactivity prescribed by Regulation 83 for the 3-way catalyst, R = 17 500, and reference temperatures T = 400 °C , 700 °C , and 800 °C , in the range of the pre-cat and post-cat temperature profiles (see Figure 8 and Figure 9), were chosen for the calculations of the total equivalent ageing time (AT) based on the methodology described in 2.2 and summarized in Table 3.

Figure 10 shows per-test equivalent ageing time (AT) originated from pre-cat and post-cat temperature profiles and taking T_{ref} = 800 °C as accelerated aging temperature, in order to obtain reasonable ageing times, i.e. in the range from few hours to few hundred hours. In addition to the per-test results, the last 3 groups of bars represent the AT for combined cold and hot start WLTC tests. This comparison exercise was included in order to deal with test of similar driven distance (about 40 km) and engine conditions: cold WLTC + hot WLTC and hot WLTC + hot WLTC should be compared with cold and hot start SRCs, respectively. The AT of combined WLTC cycles fell in the range of the single WLTC cycles, hence with no additional effect on the final assessment.

A comparison of the thermal loads linked to WLTC and SRC is shown in Figure 11. Given the limited size of the statistical sample (N=2 for SRC, and N=3 for WLTC), it can only be stated that the two groups of measurements (SRC and WLTC) look very similar as they overlap. The repeatability of the measurements however suggests that similar conclusions would hold even in the presence of a larger sample, as confirmed ex-post by the results from the other vehicles. We can conclude that for this car the WLTC and SRC cycles were very similar as far as the thermal load to the after-treatment system is concerned.

Note that the ageing times for different reference temperatures only differ in absolute values, while the discussion on relative amounts remains valid, as can be seen in the example in Figure 12 for T_{ref} = 400 °C and T_{ref} = 700 °C.

As different drivers drove the test vehicles during the measurement campaign, we checked if different driving styles had an influence on the test results. As an example, let us consider tests 4 and test 5 shown in Figure 7 and Figure 8. The speed profiles overlapped without major violations, suggesting that the test would have yielded similar results in terms of equivalent ageing times and thus thermal loads. The temperature profiles showed instead significantly divergent profiles especially during deceleration phases (end of the cycle) as highlighted by the difference of temperatures between the 2 tests displayed in Figure 13. The deceleration phases, without an agreed driving strategy, might be performed either by lifting the accelerator pedal and/or using the brakes or by a combined use of engine brakes and gear-shift. These two choices caused temperature differences as high as 200 degrees with consequence on the statistical stability of equivalent ageing time values in the order of 20% over similar valid and apparently equivalent tests. Driving styles and gear shift-strategy are interrelated subjects and their effects could be minimized. A gear-shift strategy was implemented in WLTC tests using the WLTP gear-shift calculator [10]. As an agreed gear shift strategy for SRC tests does

([10]) https://wltp.readthedocs.io/en/latest/

not exist, we developed it based on the vehicle's technical specifications and road-load parameters as shown in Figure 14. The WLTP python tool v0.1.0-alpha.3 ([11]) was used to produce the gear-shift profile. The fundamental idea of the WLTP GS algorithm is to use the maximum possible gear based on available power, modified to comply with driveability requirements (e.g. following realistic engine speed limits, avoiding too frequent gearshifts, or mimicking typical downshifts when decelerating to stop).

Concerning the driving styles harmonization, we followed the driving instructions for SRC laid down in Regulation EU 134/2014, Appendix 1, for the L-category vehicles (2-, 3-wheelers and small quadricycles).

Note that there are little chances to identify different temperature profiles from differences in vehicle emissions as highlighted in Figure 15 where CO_2 mass emissions profiles are plotted together with emission factors. The large temperature difference in the deceleration phases explained above, which was caused by lifting the accelerator pedal or by using breaks, does not affect the engine load and therefore neither the CO_2 emissions (1.6% difference between 2 tests) due to the low instantaneous exhaust flow.

Table 2. Technical specifications of vehicle 1.

Vehicle	Vehicle 1
Engine type	SI
Injection	PFI
After-treatment	TWC
EURO	EURO 6b
Fuel	E10
Displacement [cm3]	1242
Cylinders	4
Power [kW]	51
Transmission	MT
Gears	5
Mileage [km]	2500
Mass [kg]	940
Year of registration	2016

Source: JRC

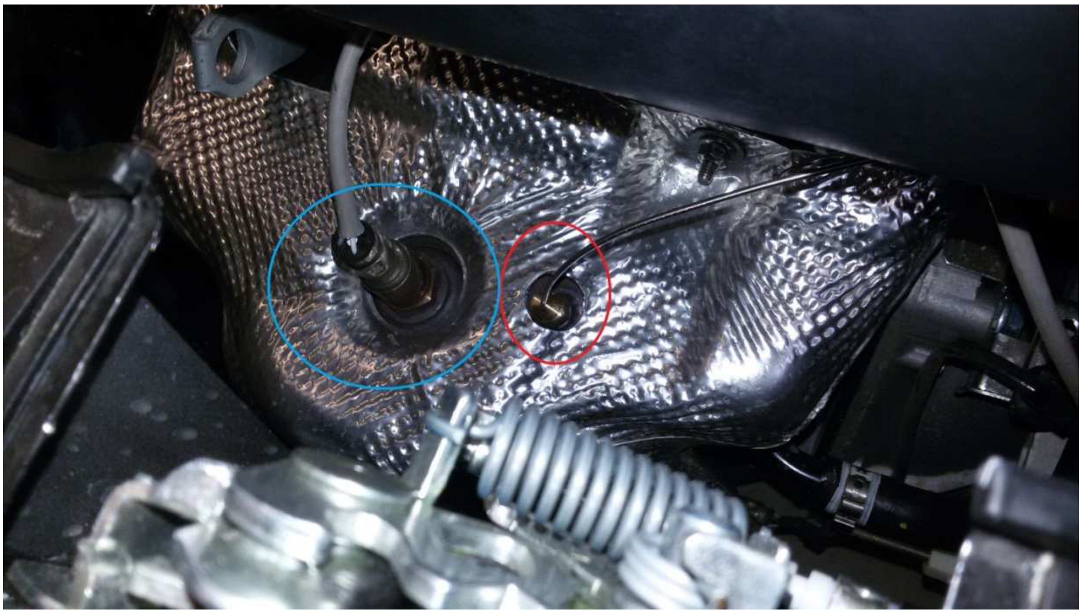
([11]) https://github.com/JRCSTU/wltp/blob/master/CHANGES.rst#id11

Table 3. Summary of test results for vehicle 1. The total ageing time (AT) is calculated for reference temperatures of 400, 700 and 800 °C.

Test No.	Vehicle	Driving Cycle	Cycle start	T Oil at t=0 [C]	Notes	AT-pre-400 [h]	AT-pre-700	AT-pre-800	AT-post-400	AT-post-700	AT-post-800
3	1	WLTC	Cold	24.5	1st cold	3.68E+06	1215.4	227.5	7.21E+06	2383.2	446.1
4	1	WLTC	Hot	99.0	1st hot	3.91E+06	1292.5	241.9	7.41E+06	2452.0	459.0
5	1	WLTC	Hot	100.8	2nd hot	3.22E+06	1065.9	199.5	7.03E+06	2323.3	434.9
6	1	SRC	Cold	22.6	1st cold	3.72E+06	1229.1	230.1	7.14E+06	2360.8	441.9
7	1	SRC	Hot	95.5	1st hot	4.23E+06	1397.9	261.7	8.15E+06	2696.2	504.7

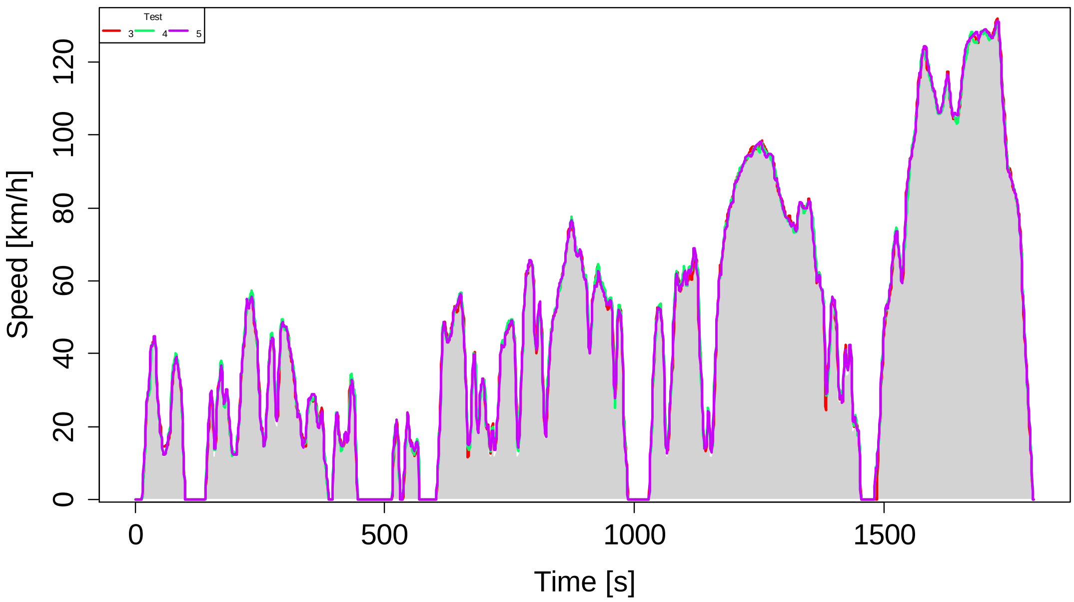
Source: JRC

Figure 6. Installation of the pre-cat thermocouple (red circle) close to the lambda sensor (blue circle) for the measurement of the temperature before the after-treatment system.



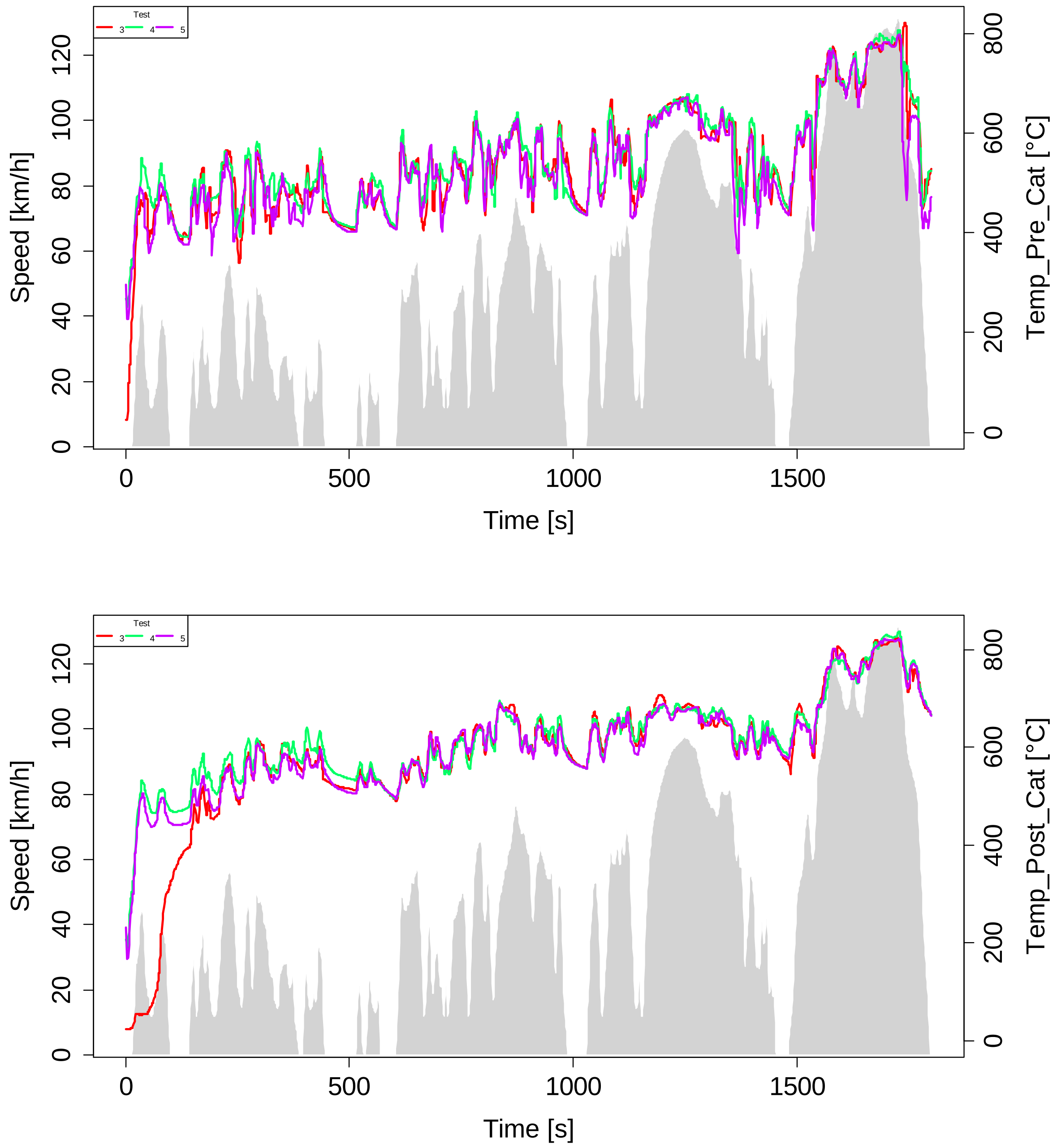
Source: JRC

Figure 7. WLTC (upper panel) and SRC (lower panel) speed profiles for all tests on vehicle 1.



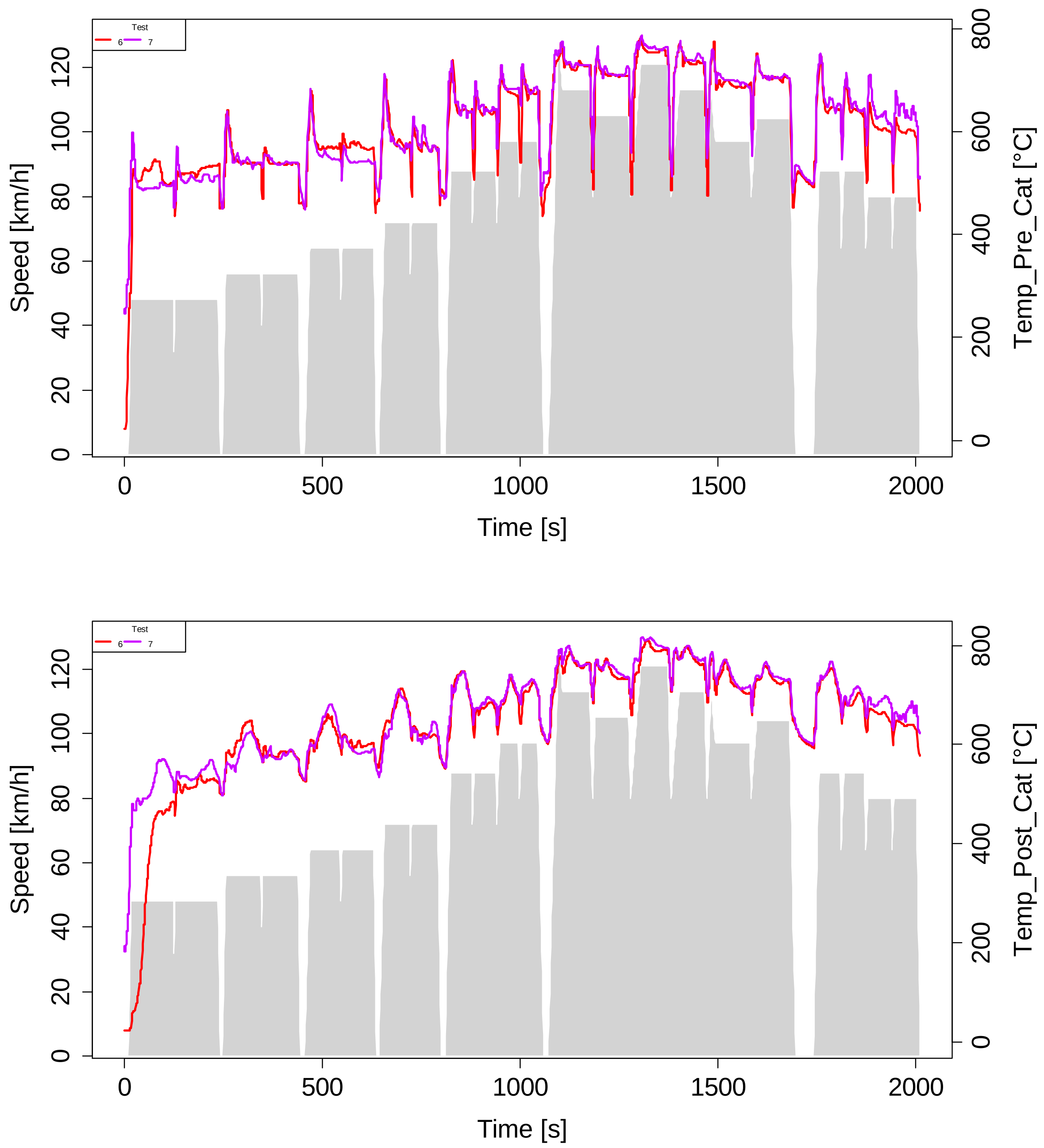
Source: JRC

Figure 8. Pre-cat (upper panel) and post-cat (lower panel) temperature profiles of WLTC tests for vehicle 1.



Source: JRC

Figure 9. Pre-cat (upper panel) and post-cat (lower panel) temperature profiles of SRC tests for vehicle 1.



Source: JRC

Figure 10. Per-test equivalent ageing time (hours) for pre-cat and post-cat temperatures with reference temperature T_{ref} = 800 °C. AT values for different reference temperatures can be found in Table 3. The last 3 groups of bars are the combined cold (C) and hot (H) start WLTC tests.

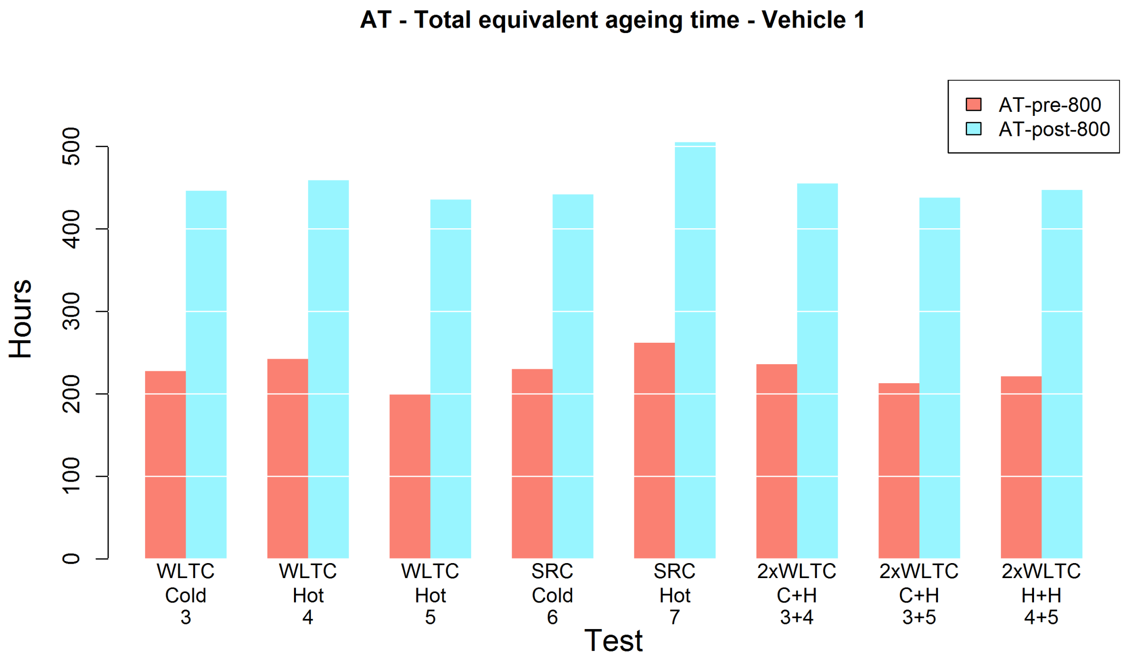
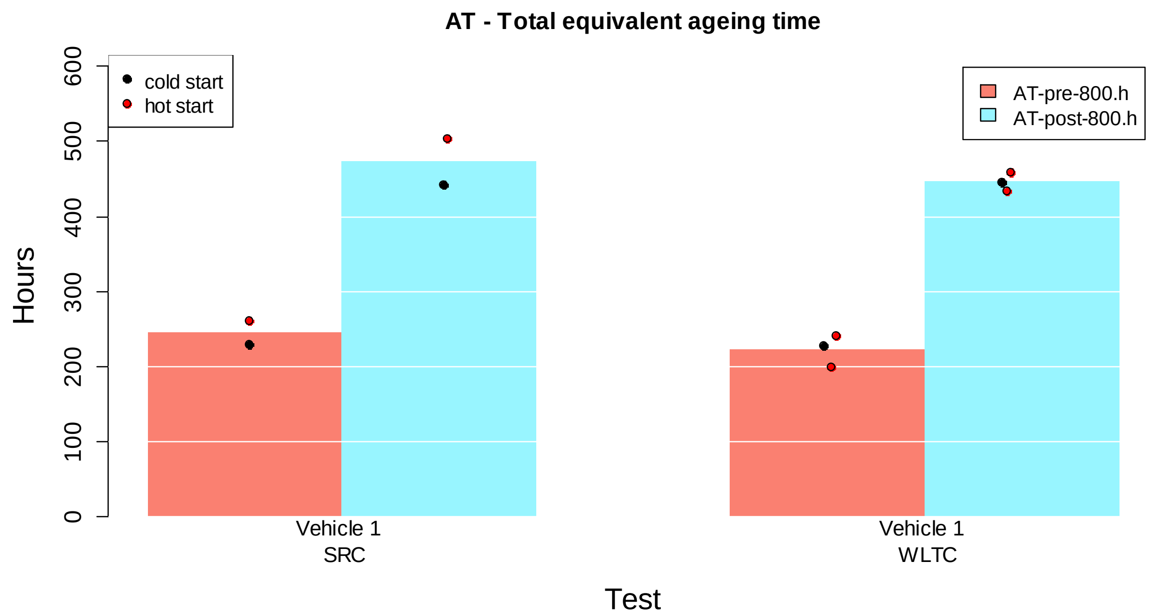
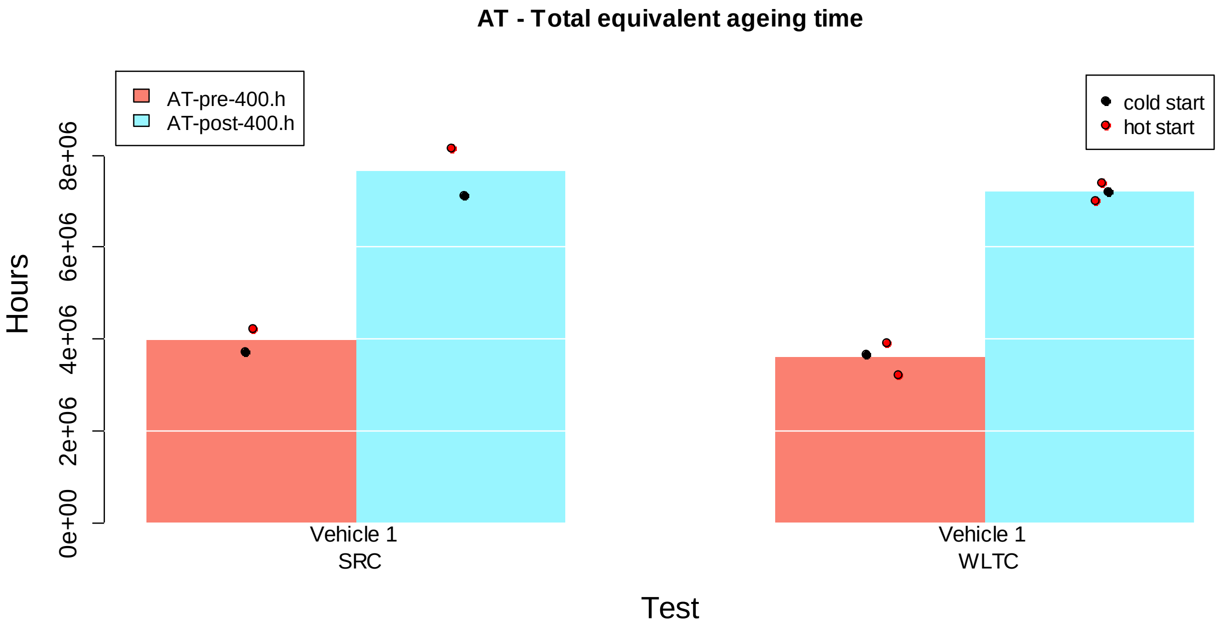


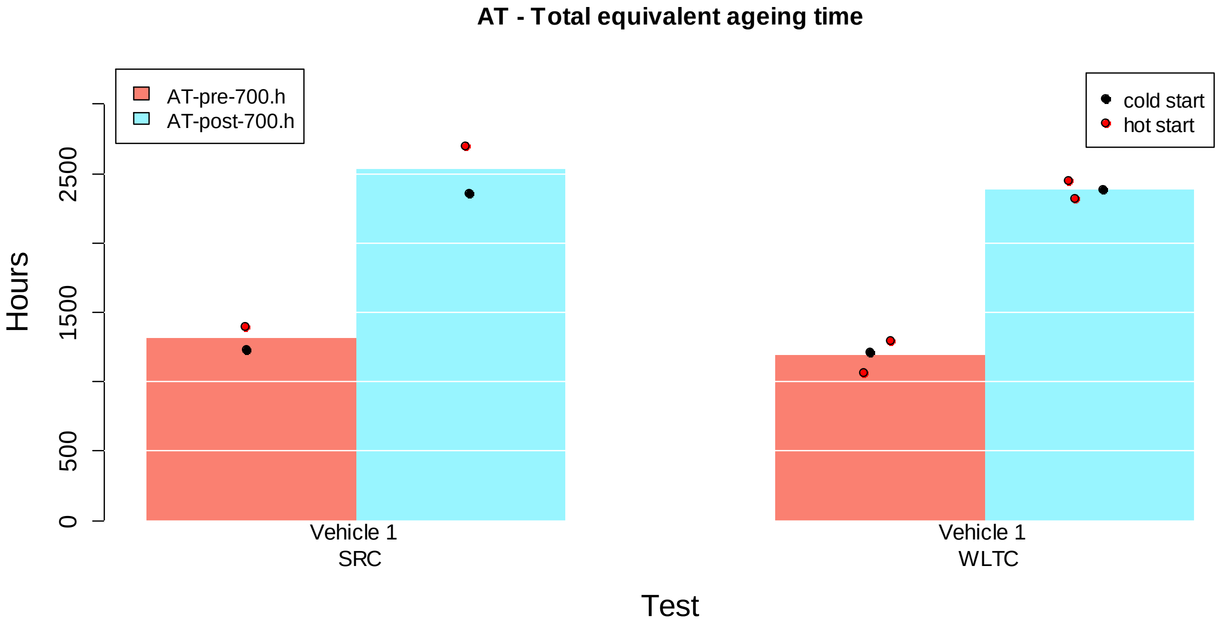
Figure 11. Summary of total equivalent ageing time, AT, for WLTC and SRC tests. Bar plots represent the average values and data points are the single cold (black) and hot (red) start tests.



Source: JRC

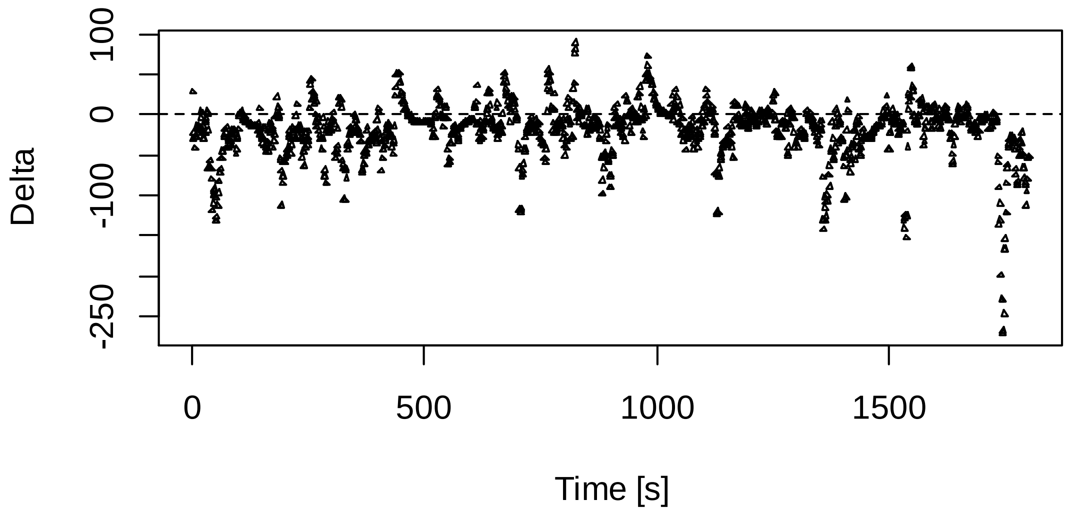
Figure 12. Example of the results obtained by varying the reference temperature in the range of pre-cat and post-cat temperatures: T_{ref}=400 °C and T_{ref}=700 °C in the left and right panels, respectively.





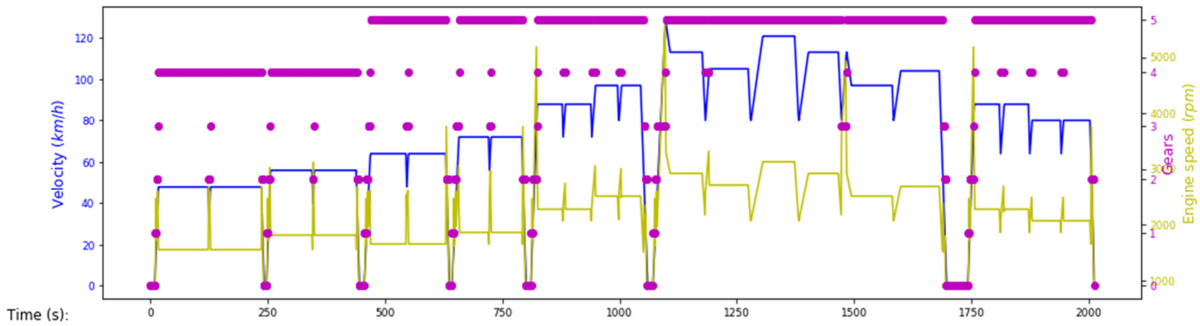
Source: JRC

Figure 13. Absolute deviation (in degrees) between temperature profiles of Test 4 and Test 5, WLTC hot-start tests with similar speed profiles.



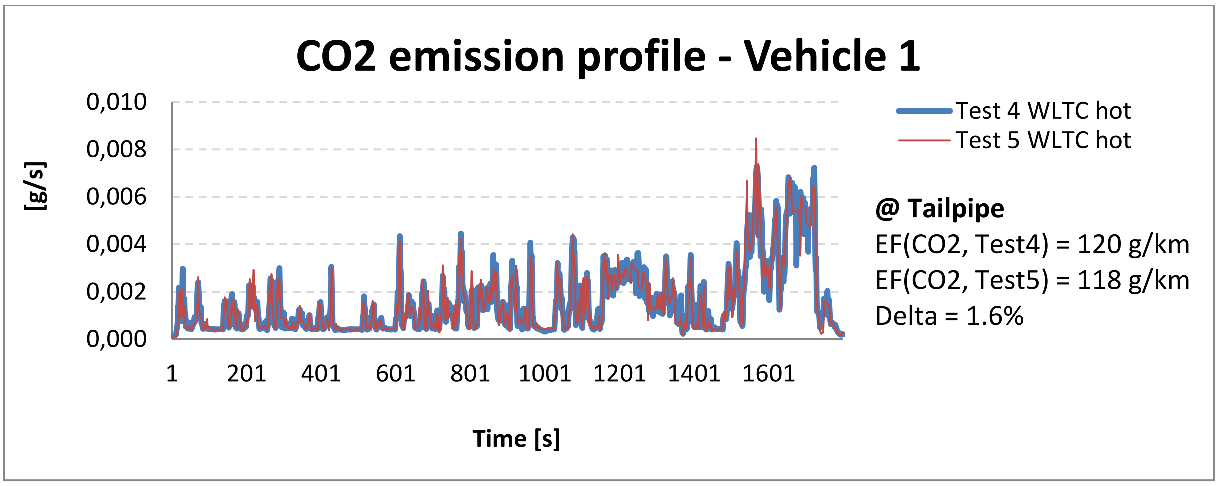
Source: JRC

Figure 14. Example of gear-shift strategy (purple) on the speed profile of an SRC (blue).



Source: JRC

Figure 15. Example of 2 tests with very similar speed profiles and emissions (within 2%) but different temperature profiles and thus different ageing times (about 20% difference). EF= emission factor.



Source: JRC

3.2 Vehicle 2

The technical specifications of vehicle 2, extracted from Table 1, are presented in Table 4. This gasoline direct injection passenger car was equipped with a 3-way catalyst and designed to run in the stoichiometric region of the air/fuel ratio. A first thermocouple (pre-cat) was installed at engine-out, before the after-treatment system and it is shown in Figure 16. A second thermocouple (post-cat) was installed under the vehicle floor after the after-treatment system. 7x WLTC and 4x SRC cycles were run following the test matrix in Table 5 without major violations, as can be seen in Figure 17 which reports overlapped speed profiles for all tests.

The thermal reactivity prescribed by UNECE Regulation No 83 for the 3-way catalyst, R = 17 500, and reference temperatures T_{ref} = 400, 700 and 800 °C, in the range of the pre-cat and post-cat temperature profiles (see Figure 18 and Figure 19), were chosen for the calculations of the total equivalent ageing time based on the methodology described in 2.2 and reported in Table 4.

Figure 20 shows per-test equivalent ageing times related to pre-cat and post-cat temperature profiles with chosen reference T_{ref} = 800 °C in order to obtain reasonable ageing times, i.e. in the range from few hours to few hundred hours.

A comparison of the thermal loads linked to WLTC and SRC is shown in Figure 21. While at first glance the SRC seems related to slightly larger AT than WLTC, a closer look at the intervals of values and results from a statistical t-test with 95% confidence interval (p-value = 0.099) tell us that the SRC and WLTC may be equal in terms of thermal load to after-treatment systems. Note that the ageing times for different reference temperatures only differ in absolute values, while the related discussion remains valid.

Figure 16. Installation of the pre-cat thermocouple close to the lambda sensor (upper figure) and post-cat thermocouple (lower figure) for the measurement of the temperatures before and after the after-treatment system.

Source: JRC

Table 4. Technical specifications of vehicle 2.

Vehicle	Vehicle 1
Engine type	SI
Injection	GDI-s
After-treatment	TWC
EURO	EURO 6b
Fuel	E10
Displacement [cm3]	999
Cylinders	3
Power [kW]	77
Transmission	MT
Gears	6
Mileage [km]	3700
Mass [kg]	1260
Year of registration	2017

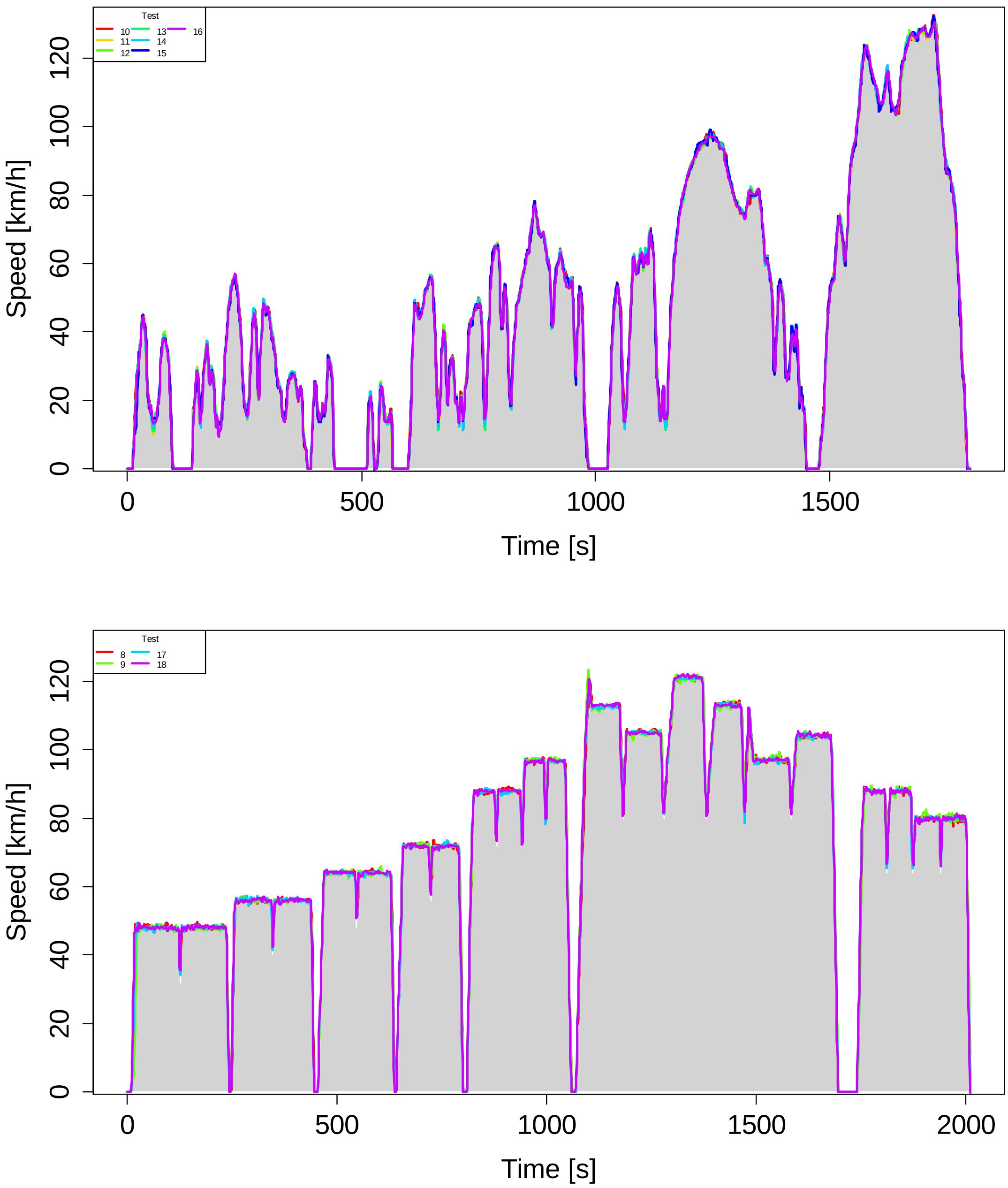
Source: JRC

Table 5. Summary of test results for vehicle 2. The total ageing time (AT) is calculated for reference temperatures of 400, 700 and 800 °C.

Test No.	**Vehicle**	**Driving Cycle**	**Cycle start**	**T Oil at t=0**	**Notes**	**AT-pre-400**	**AT-pre-700**	**AT-pre-800**	**AT-post-400**	**AT-post-700**	**AT-post-800**
				[C]				**[h]**			
8	2	SRC	Cold	23.9	1st cold	1.53E+06	507.0	94.9	2.81E+06	928.8	173.9
9	2	SRC	Hot	102.5	1st hot	1.73E+06	571.3	106.9	3.06E+06	1012.9	189.6
10	2	WLTC	Cold	23.7	1st cold	1.39E+06	460.7	86.2	2.22E+06	733.9	137.4
11	2	WLTC	Hot	80.5	1st hot	1.29E+06	425.6	79.7	1.95E+06	644.6	120.7
12	2	WLTC	Hot	91.6	2nd hot	1.39E+06	458.2	85.8	2.06E+06	682.0	127.6
13	2	WLTC	Cold	25	2nd cold	1.91E+06	632.1	118.3	2.64E+06	874.5	163.7
14	2	WLTC	Hot	83.8	3rd hot	1.71E+06	565.6	105.9	2.35E+06	777.1	145.5
15	2	WLTC	Cold	22.9	3rd cold	1.40E+06	462.9	86.6	2.18E+06	719.6	134.7
16	2	WLTC	Hot	80.1	4th hot	1.46E+06	481.8	90.2	2.23E+06	736.3	137.8
17	2	SRC	Cold	21.5	2nd cold	2.35E+06	777.7	145.6	3.21E+06	1060.7	198.5
18	2	SRC	Hot	99.4	2nd hot	2.27E+06	751.1	140.6	3.25E+06	1074.4	201.1

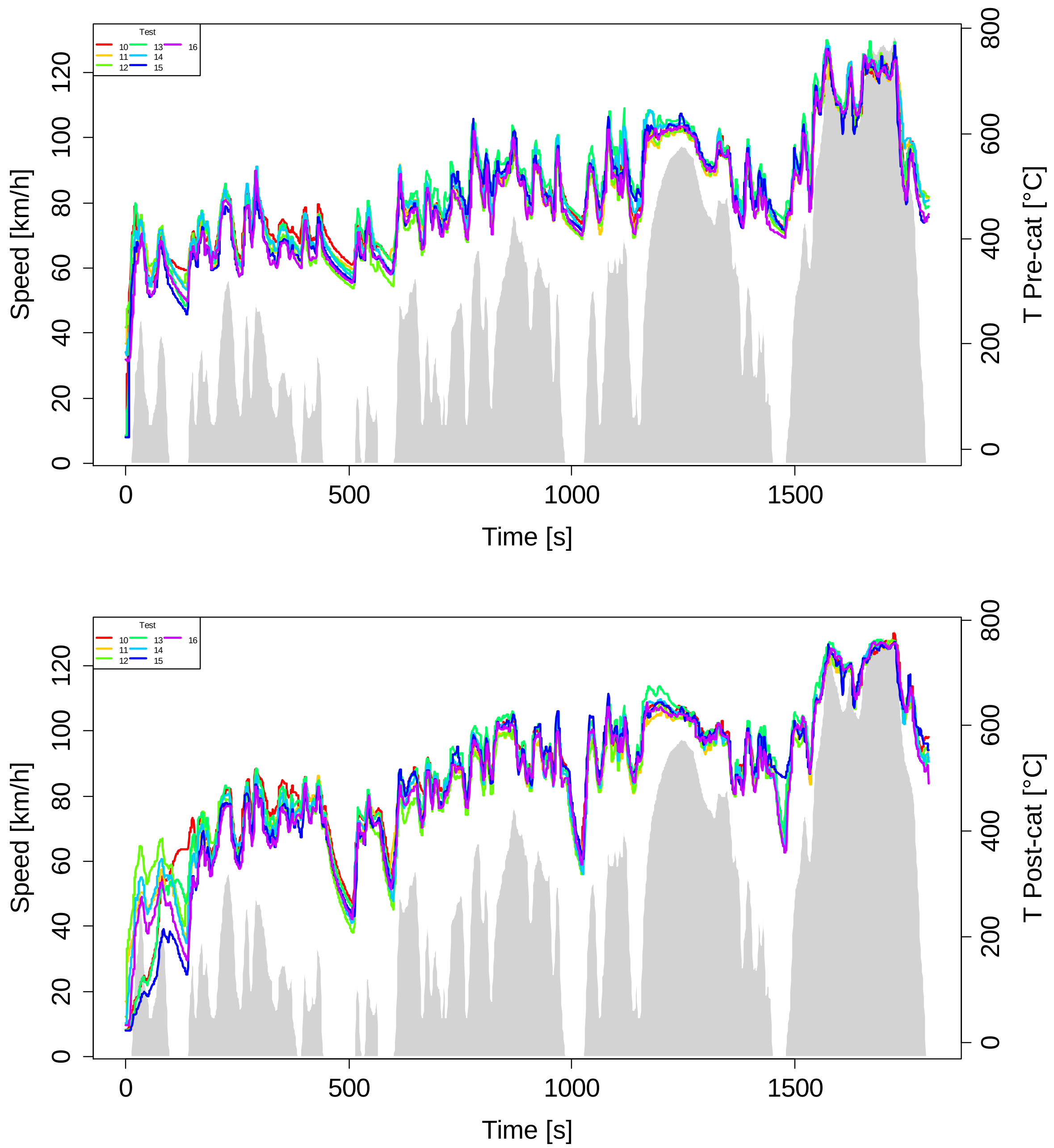
Source: JRC

Figure 17. WLTC (upper panel) and SRC (lower panel) speed profiles for all tests on vehicle 2.



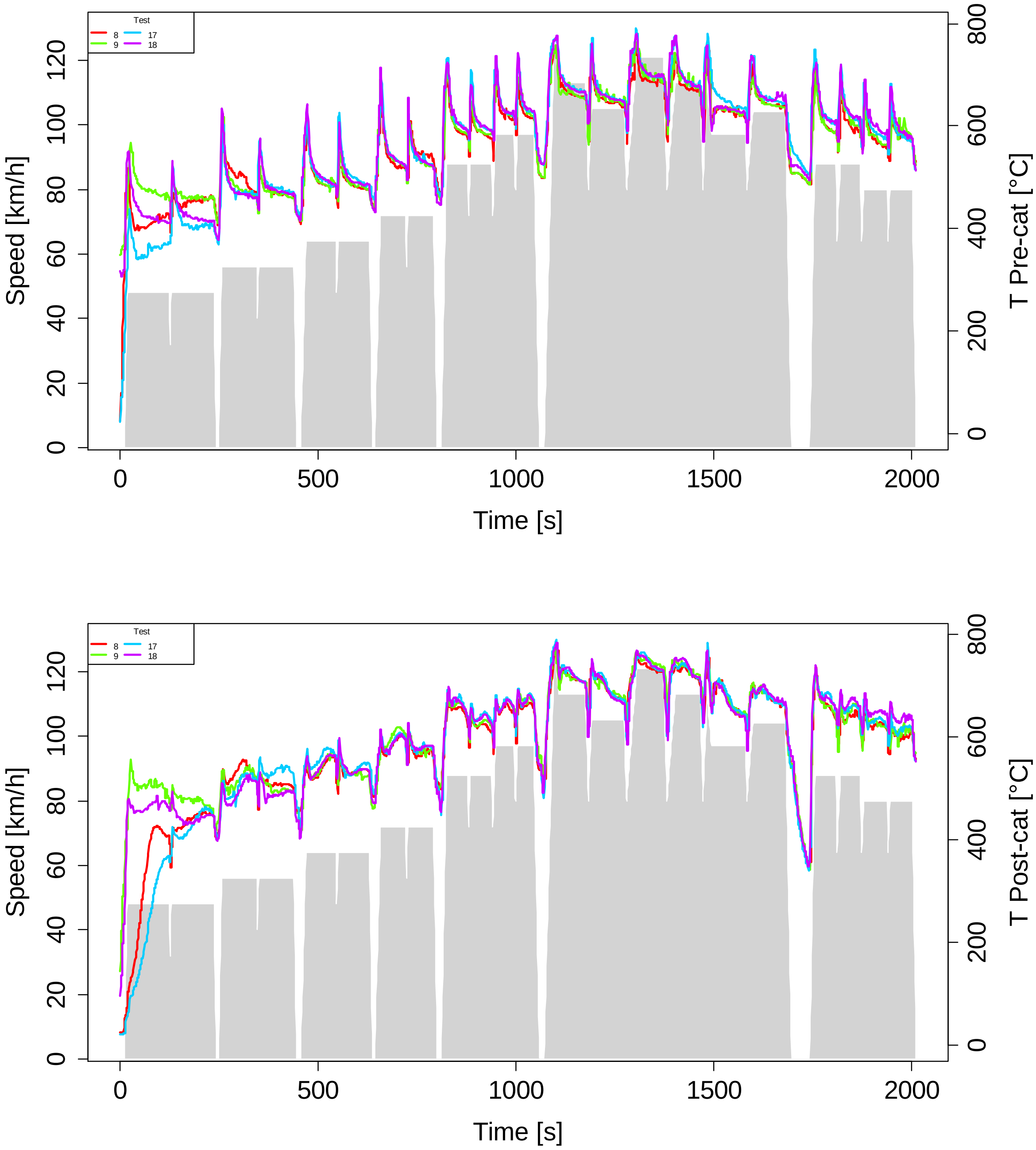
Source: JRC

Figure 18. Pre-cat (upper panel) and post-cat (lower panel) temperature profiles of WLTC tests for vehicle 2.



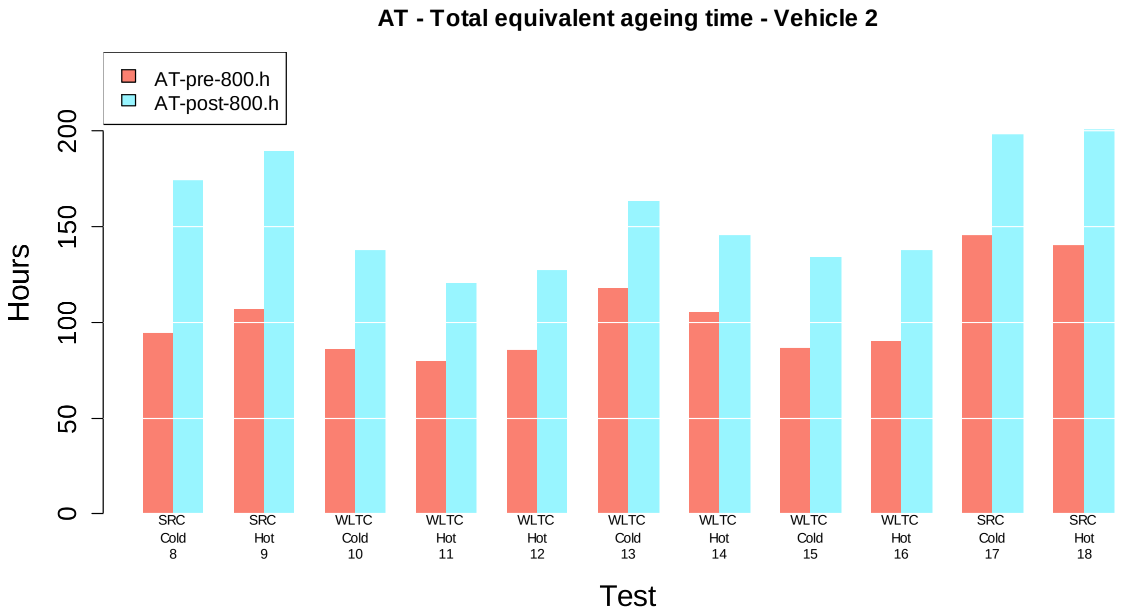
Source: JRC

Figure 19. Pre-cat (upper panel) and post-cat (lower panel) temperature profiles of SRC tests for vehicle 2.



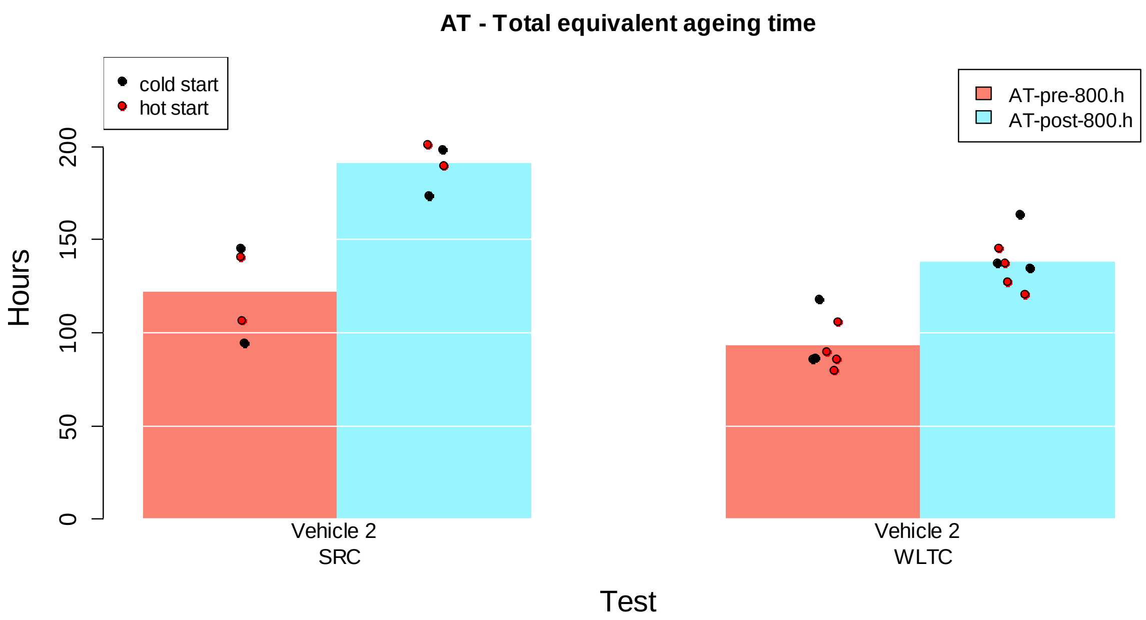
Source: JRC

Figure 20. Per-test equivalent ageing time (AT, in hours) for pre-cat and post-cat temperatures with reference temperature T_{ref} = 800 °C. AT values for different reference temperatures can be found in Table 5.



Source: JRC

Figure 21. Summary of total equivalent ageing time, AT, for WLTC and SRC tests of vehicle 2. Bar plots represent the average values and data points are the single cold (black) and hot (red) start tests.



Source: JRC

3.3 Vehicle 3

The technical specifications of vehicle 3, extracted from Table 1, are presented in Table 6. This compressed ignition passenger car was equipped with diesel oxidation catalyst for the oxidation of hydrocarbons and carbon monoxide, a DPF for particle mass reduction, and a lean-NOx trap for NOx reduction. Only the post-cat thermocouple was installed under the vehicle and after the after-treatment system. Any intervention to install a pre-cat thermocouple would have required major dismantling of mechanical part which was not carried out in our emission lab. In addition to the post-cat thermocouple, we acquired the variables "Catalyst Temperature Bank 1, Sensor 1 [°C]" and "Catalyst Temperature Bank 1, Sensor 2 [°C]" from the OBD system. After discussion with the vehicle manufacturer, we could associate the 2 OBD signals to pre-cat and post-cat temperature signals, before and after the entire series of DOC-LNT-DPF after-treatment systems. The former signal was used as pre-cat temperature instead of a pre-cat thermocouple. A comparison of post-cat thermocouple and OBD signal "Sensor 2" is shown in Figure 22 for confirmation: the post-cat thermocouple signal and Sensor 2 show similar patterns with generally lower temperatures from the downstream source, as expected given the downstream position of the post-cat thermocouple.

23x WLTCs and 6x SRCs cycles were run following the test matrix given in Table 7 without major violations, as can be seen in Figure 23 which reports overlapped speed profiles for all the tests. The larger number of tests compared to the previous vehicles is related to the procedure described in section 2.2 where a number of tests should be run until regeneration of the diesel particle filter occurs, the frequency of which was a-priori unknown.

A thermal reactivity related to the diesel oxidation catalyst, R = 18 050, and reference temperatures T = 400 700 and 800 °C, in the range of the pre-cat and post-cat temperature profiles (see Figure 24 and Figure 25), were chosen for the calculations of the total equivalent ageing time based on the methodology described in section 2.2 and reported in Table 7. As far as we are aware of, single tabulated chemical reactivity values referred to multiple after-treatment devices mounted in series do not exist and would have limited use. As we could deploy only 2 thermocouples before and after the entire after-treatment block, the only choice is to use a single value of chemical reactivity related to one or more of the after-treatment devices. In the case of vehicle 3 equipped with DOC-LNT-DPF, the only possible choice is R = 18 050 which is the same for the 3 components separately: DOC, LNT and catalysed DPF (see for instance Regulation (EU) 2016/1718). A related study commissioned by DG-GROWTH and performed in parallel to the present one by an external lab which uses engine test bench should in the next future elucidate the intra-ATS thermal loads and reactivity.

The DPF active regeneration is performed by additional fuel injection, normally at the end of the expansion phase of the cylinder, so that this fuel burns in the filter and provides the heat to start the combustion of the deposited carbon. Therefore, temperature profiles, in particular post-cat temperature in Figure 24 and Figure 25 are useful to identify the tests in which the regeneration of the DPF took place. The DPF regenerated during WLTC tests 41, 42 and 50 in the extra-high speed phase, and during the end of the SRC test 33. In all cases the DPF regeneration occurred at time t ≈ 1600-1700 sec after cycle start, indicating very similar conditions of engine and ATS input parameters handled by the DPF management system. The DPF regenerations were not related to the driving cycle type or to the initial conditions of the cycle, cold or hot start. The cold and hot start cycles differed only in the first 0-100 sec of the T_pre-cat profiles and 0-400 sec of the T_post-cat profiles when temperatures are generally below 300 C, with low impact on the ageing time.

As an additional confirmation of DPF regeneration besides temperature profiles, a particle number (PN) measurement system complying with the requirements laid down in UNECE Regulation 83 was deployed to sample diluted exhaust. Figure 26 and Figure 27 show the particle number measurements for WLTC and SRC tests. DPF regenerations are confirmed by the large PN values at the end of the cycles, while large PN values at the beginning of the tests are caused by the cold start test conditions. The larger PN values reached during DPF regeneration in the SRC test 33 compared to those of WLTC should depend on the history of vehicle operation between 2 regenerations; long periods of steady state driving (SRC) would accumulate more material on the filter than during the more dynamic WLTCs.

Total equivalent ageing times (AT) are summarized in Table 7 and Figure 28 (upper panel for WLTC and lower panel for SRC) indicating a large sensitivity with respect to the reference temperature, with AT spanning 3 orders of magnitude for T_{ref} in the range 400-800 °C. It is clear that the thermal load related to tests with DPF regeneration is much larger than in tests without DPF regeneration, especially if the post-cat temperature is considered: 16 times and 270 times larger for WLTC pre-cat and post-cat temperatures, respectively, and 3 times and 170 times larger for SRC pre-cat and post-cat temperatures, respectively.

We observed an average mileage between regenerations of about 230 km, meaning that during the useful life of the vehicle (160 000 km) the DPF of vehicle 3 (and downstream components of the ATS) would experience about 700 regenerations. This behaviour is very different from vehicle 4 which was subject to much less frequent regenerations (every 800-1000 km, see section 3.4).

Excluding the tests with DPF regenerations, the SRC tests featured larger AT than WLTC tests, as can be seen in Figure 29 which also suggests large inter-test variability in terms of AT (coefficient of variation for WLTCs ≈ 60%). As expected, while T_pre-cat was larger than T_post-cat in tests without DPF regeneration, the opposite occurred in tests with DPF regeneration, due to high temperatures reached by the DPF.

A closer look to Figure 24 and Figure 25 highlights several spikes in the temperature profiles, especially during the SRC tests. The more dynamic speed profile of the WLTCs compared to SRCs partially hindered the spikes. These spikes lasted 1-2 minutes and happened randomly in each test, well distinct from the temperature peaks after intense accelerations. They are not associated to different engine conditions or driving pattern, as both the engine and the vehicle speed profiles were very similar in all tests. We ascribe them to LNT regeneration and/or DPF aborted regenerations. Whatever their cause, they are responsible for the large variability observed in AT results of Figure 30. In the case of vehicle 3, the variability related to different driving styles (and/or different drivers) observed and discussed in section 3.1 was minimized by implementing the SRC driving instructions of Regulation EU 134/2014. Moreover, being an automatic transmission passenger car, vehicle 3 did not need the implementation of a gear-shift strategy for SRC as in the case for the other test vehicles. A statistical t-test with 95% confidence level yields p-value << 0.05 with averaged AT = 3903 hours and AT=1169 hours for SRC and WLTC, respectively, excluding tests with DPF regenerations and for T_{ref} = 400 °C, indicating that the SRC and WLTC AT differs and the SRC is more severe in terms of thermal load.

Table 6. Technical specifications of vehicle 3.

Vehicle	Vehicle 1
Engine type	CI
Injection	DI
After-treatment	DOC, LNT, DPF
EURO	EURO 6b
Fuel	B7
Displacement [cm3]	1461
Cylinders	4
Power [kW]	66
Transmission	AT
Gears	--
Mileage [km]	21190
Mass [kg]	1279
Year of registration	2017

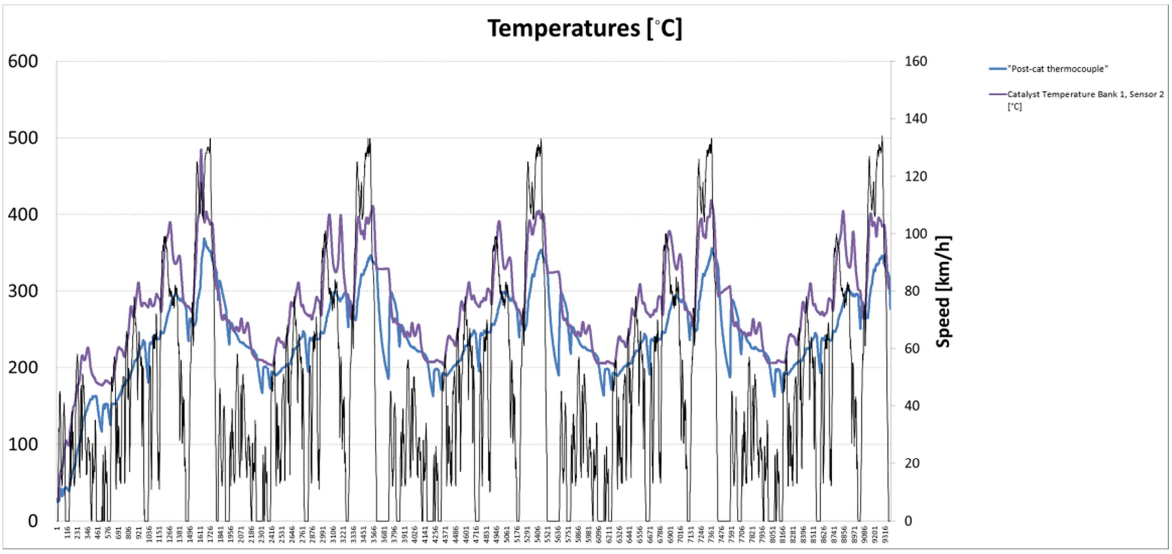
Source: JRC

Table 7. Summary of test results for vehicle 3. The total ageing time (AT) is calculated for reference temperatures of 400, 700 and 800 °C.

Test No.	Vehicle	Driving Cycle	Cycle start	T Oil at t=0 [C]	Notes	AT-pre-400 [h]	AT-pre-700	AT-pre-800	AT-post-400	AT-post-700	AT-post-800
20	3	WLTC	Cold	25.6	1st cold	2176.5	0.6	0.1	1055.6	0.3	0.0
21	3	WLTC	Hot	96.35	1st hot	588.2	0.1	0.0	427.4	0.1	0.0
22	3	WLTC	Hot	94.6	2nd hot	395.3	0.1	0.0	373.6	0.1	0.0
23	3	WLTC	Hot	95.5	3rd hot	383.7	0.1	0.0	372.9	0.1	0.0
24	3	WLTC	Hot	95.2	4th hot	505.9	0.1	0.0	365.2	0.1	0.0
25	3	SRC	Cold	22.3	1st cold	4113.0	1.1	0.2	2173.0	0.6	0.1
26	3	SRC	Hot	87.5	1st hot	3852.8	1.0	0.2	2355.4	0.6	0.1
27	3	SRC	Hot	91.3	2nd hot	4113.8	1.1	0.2	2629.8	0.7	0.1
31	3	SRC	Cold	22	2nd cold	4535.7	1.2	0.2	2481.8	0.6	0.1
32	3	SRC	Hot	88.1	3rd hot	2919.4	0.7	0.1	2072.9	0.5	0.1
33	3	SRC	Hot	88	4th hot Regeneration	11589.4	3.0	0.5	389728.2	100.2	17.8
34	3	WLTC	Hot	46.9	5th hot	637.2	0.2	0.0	399.7	0.1	0.0
35	3	WLTC	Hot	96.7	6th	1830.3	0.5	0.1	1146.3	0.3	0.1
36	3	WLTC	Hot	94.2	7th	519.7	0.1	0.0	550.2	0.1	0.0
37	3	WLTC	Hot	94.4	8th	726.7	0.2	0.0	712.4	0.2	0.0
38	3	WLTC	Hot	93.7	9th	683.0	0.2	0.0	811.4	0.2	0.0
39	3	WLTC	Hot	79	10th	772.1	0.2	0.0	608.2	0.2	0.0
40	3	WLTC	Hot	97.1	11th	847.0	0.2	0.0	820.9	0.2	0.0
41	3	WLTC	Cold	24.5	2nd cold Regeneration	4633.4	1.2	0.2	89802.1	23.1	4.1
42	3	WLTC	Hot	69.4	12th hot Regeneration	20750.2	5.3	0.9	262702.9	67.5	12.0
43	3	WLTC	Cold	24.5	3rd cold	1928.8	0.5	0.1	1584.6	0.4	0.1
44	3	WLTC	Hot	84.7	13th hot	1259.3	0.3	0.1	1306.9	0.3	0.1
45	3	WLTC	Hot	66.8	14th hot	1364.6	0.3	0.1	1638.3	0.4	0.1
46	3	WLTC	Cold	33.3	4th cold	1036.3	0.3	0.0	1498.2	0.4	0.1
47	3	WLTC	Hot	90.8	15th hot	2251.1	0.6	0.1	1113.5	0.3	0.1
48	3	WLTC	Cold	25.4	5th cold	3195.9	0.8	0.1	2291.2	0.6	0.1
49	3	WLTC	Hot	86	16th hot	858.0	0.2	0.0	699.1	0.2	0.0
50	3	WLTC	Hot	40.8	17th hot Regeneration	29223.0	7.3	1.3	434078.0	111.6	19.8
51	3	WLTC	Hot	72.2	18th hot	1422.4	0.4	0.1	1572.1	0.4	0.1

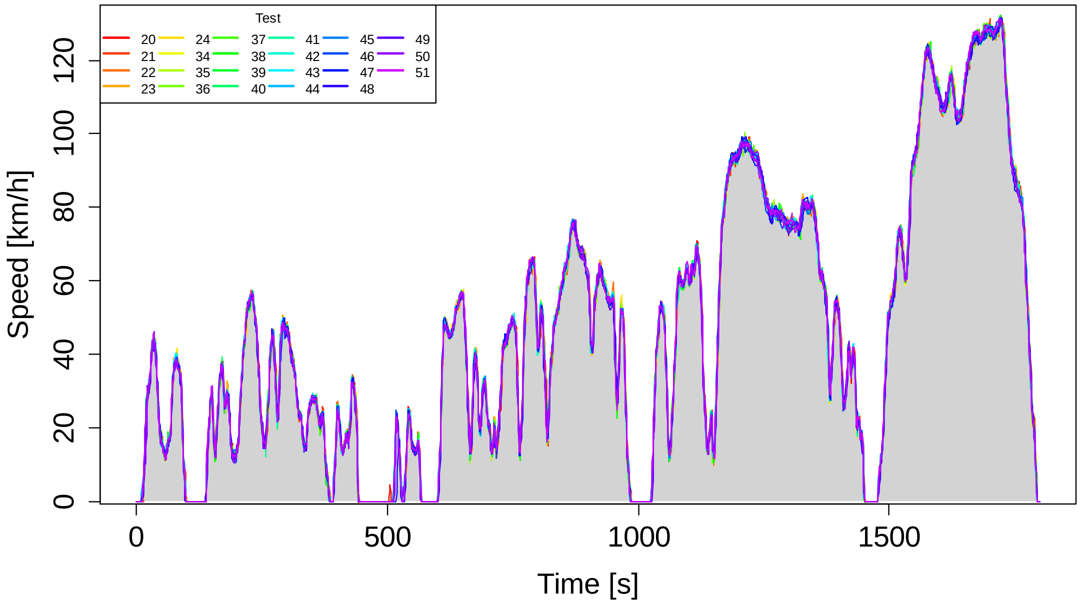
Source: JRC

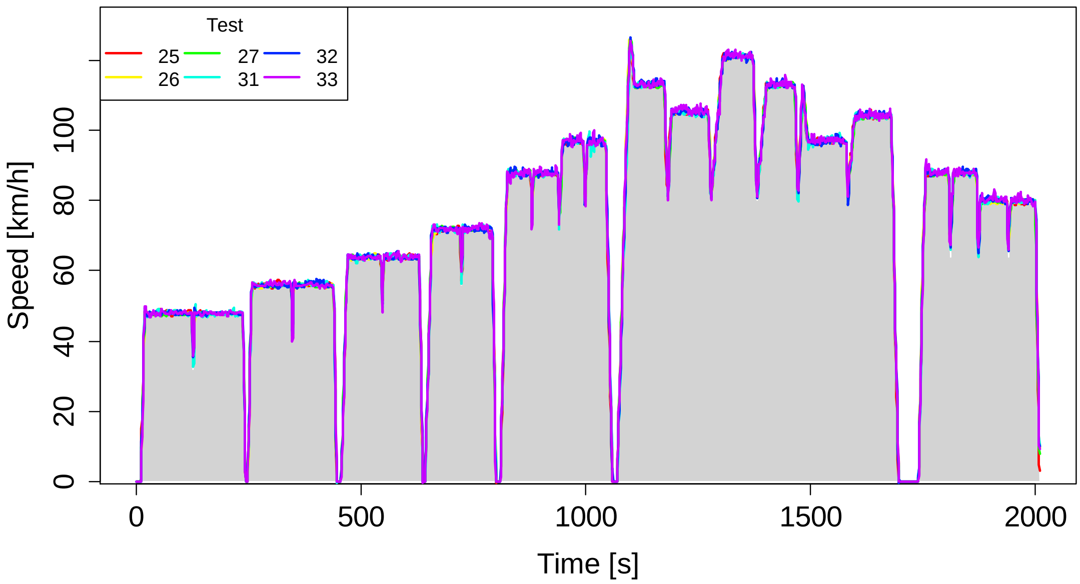
Figure 22. Comparison of post-cat thermocouple (blue line) and OBD Sensor 2 (purple line) over 5x WLTC tests. The WLTC speed trace is plotted for guidance (black line).



Source: JRC

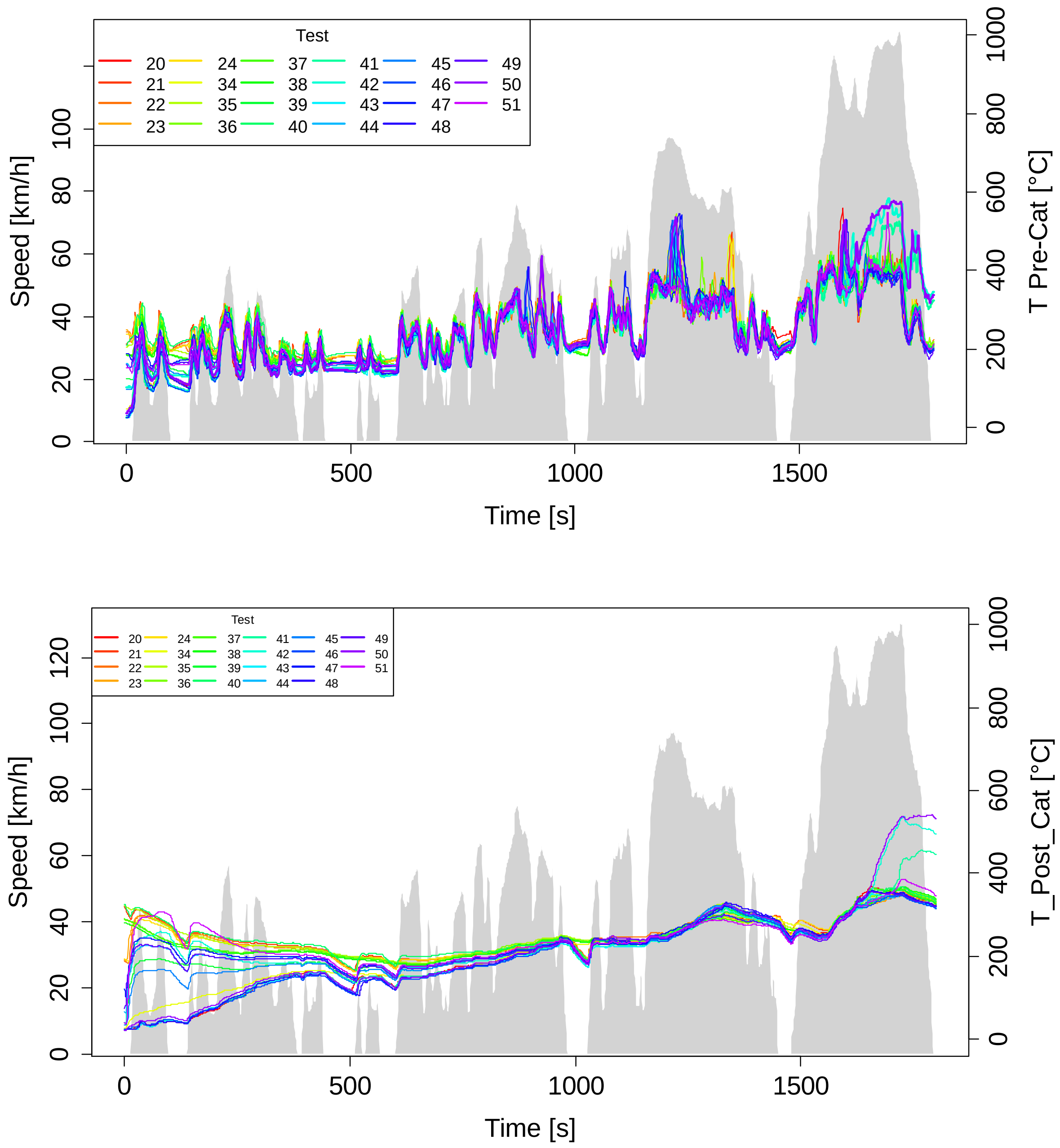
Figure 23. WLTC (upper panel) and SRC (lower panel) speed profiles for all tests on vehicle 3.





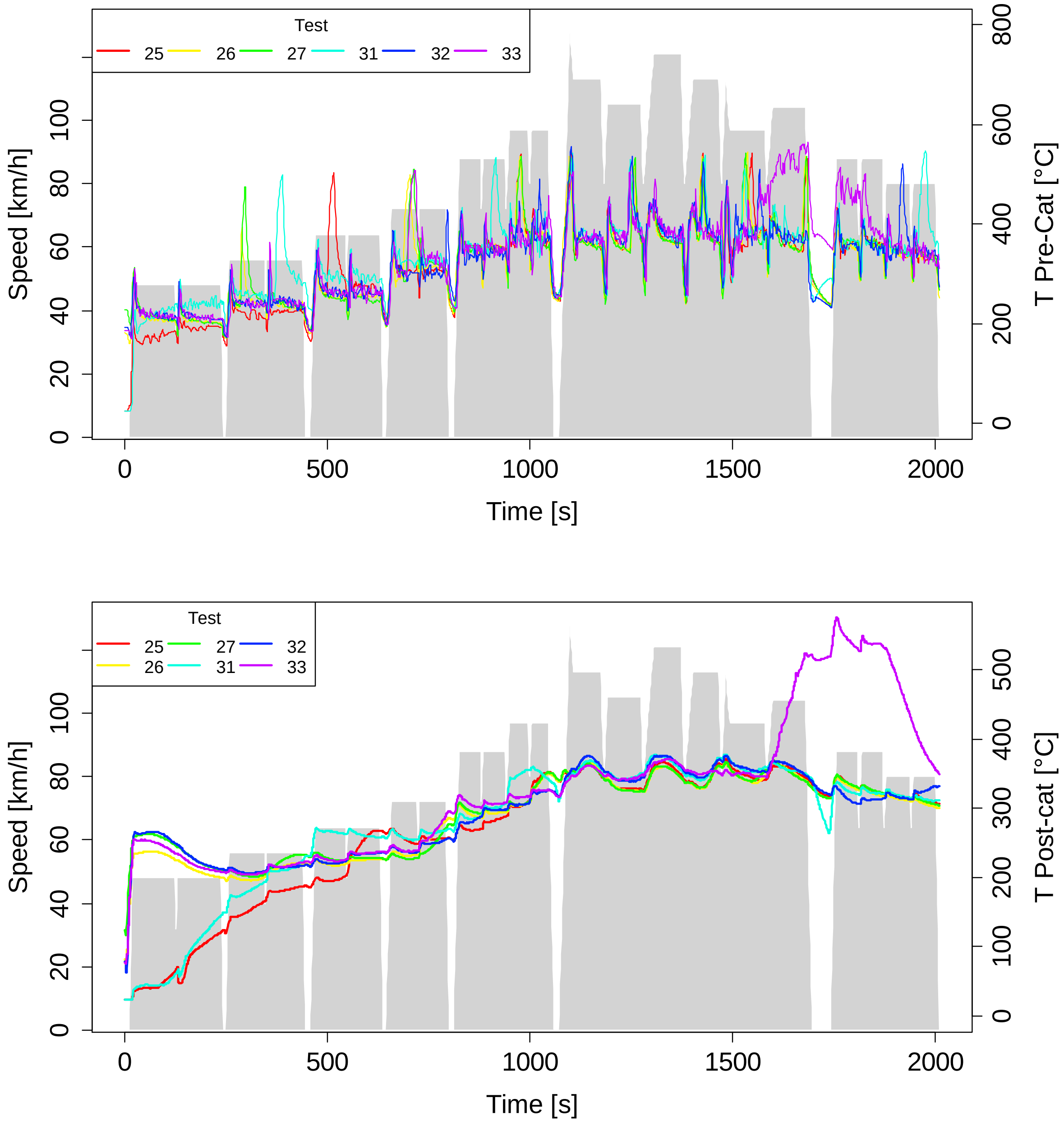
Source: JRC

Figure 24. Pre-cat (upper panel) and post-cat (lower panel) temperature profiles of WLTC tests for vehicle 3.



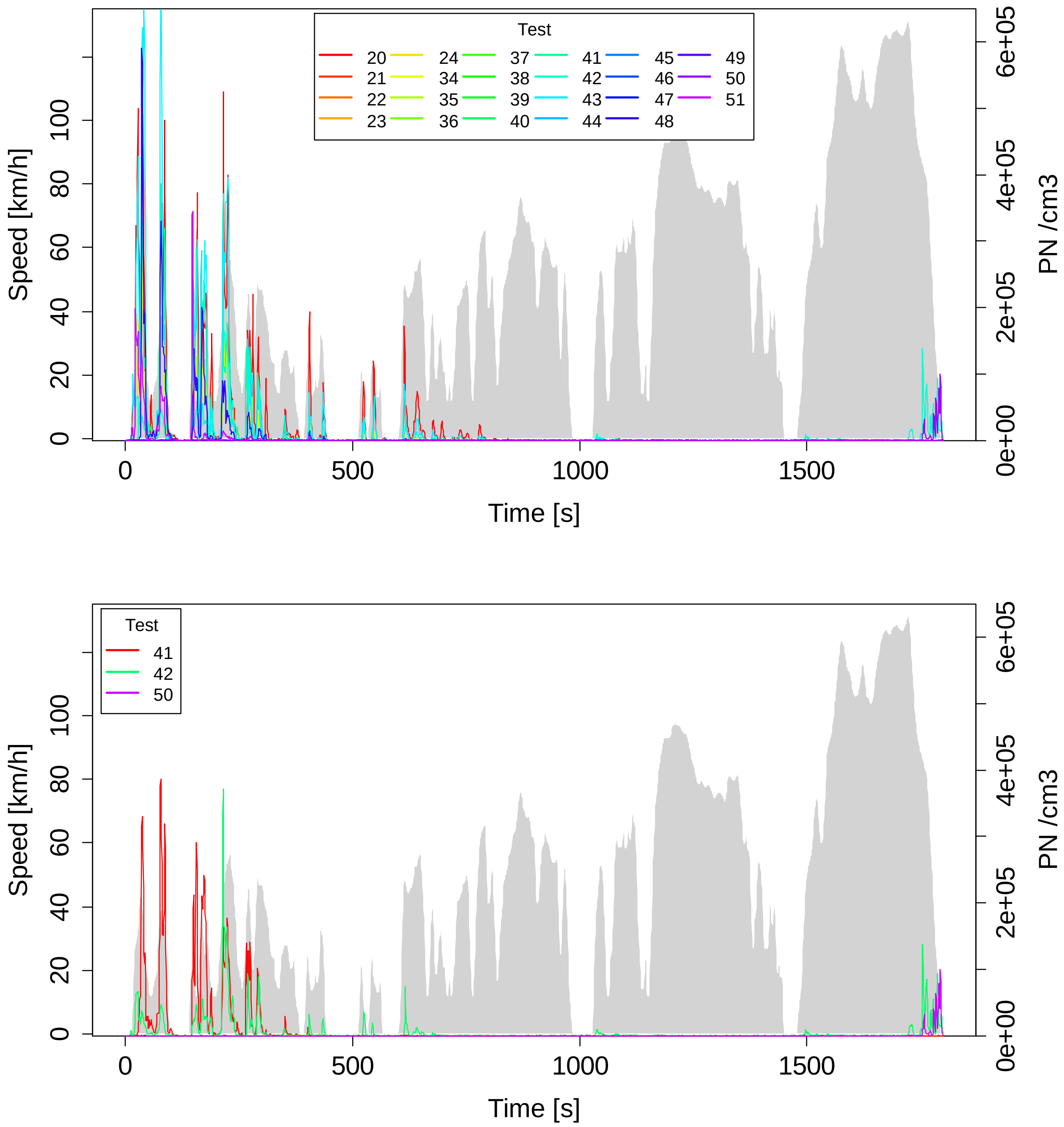
Source: JRC

Figure 25. Pre-cat (upper panel) and post-cat (lower panel) temperature profiles of SRC tests for vehicle 3.



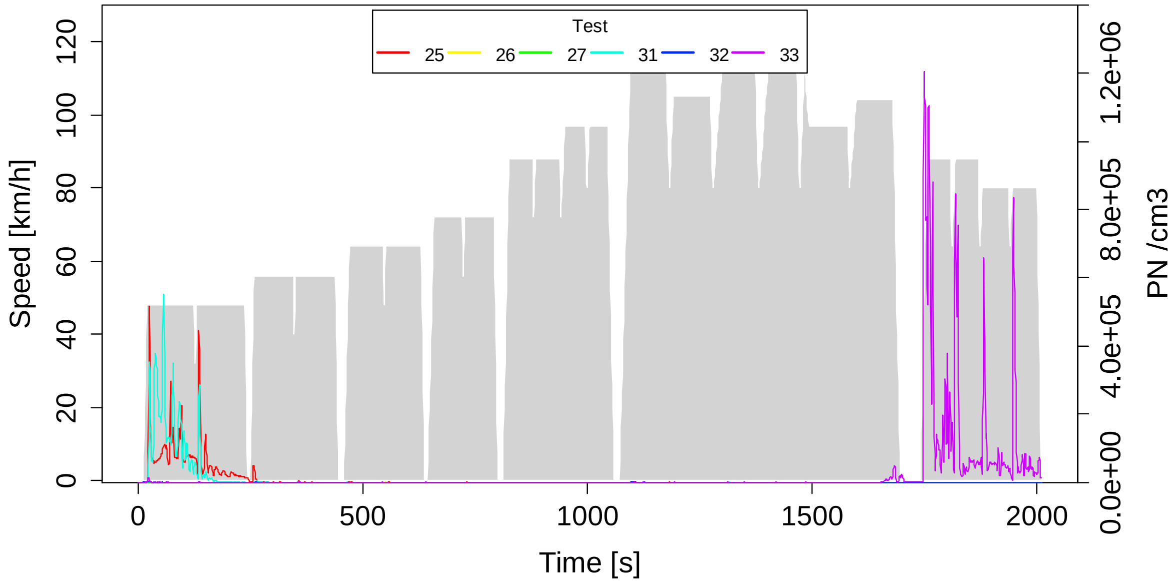
Source: JRC

Figure 26. Particle number measurements for all WLTC tests (upper panel) on vehicle 3 and only tests with DPF regeneration (lower panel).



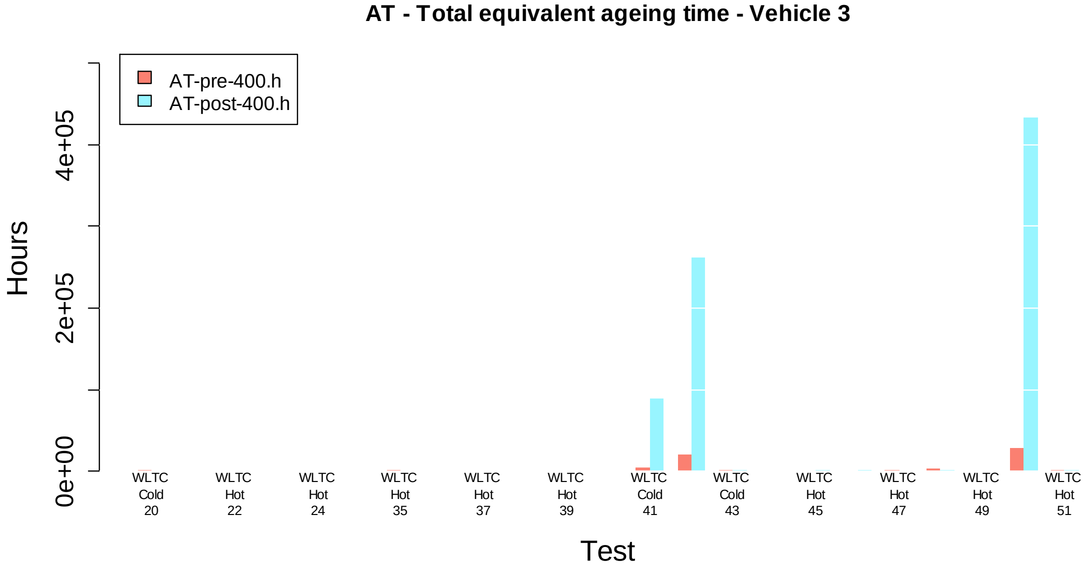
Source: JRC

Figure 27. Particle number measurements for all SRC tests on vehicle 3.

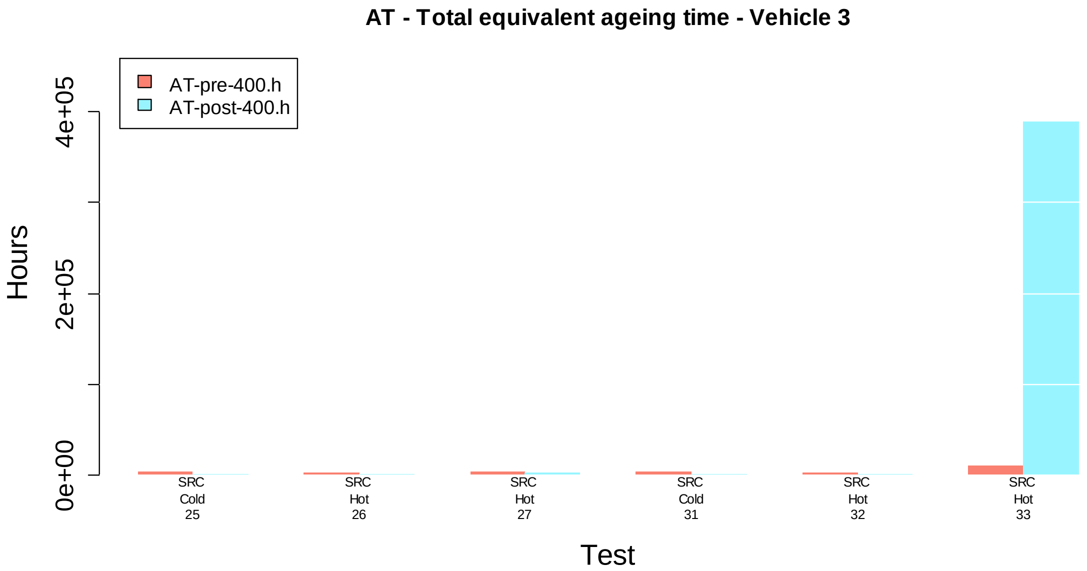


Source: JRC

Figure 28. Per-test equivalent ageing time (hours) for pre-cat and post-cat temperatures with reference temperature T_{ref} = 400 °C: WLTC tests in upper panel, SRC tests in lower panel. The largest values are related to tests where regeneration took place (tests number 41, 43, and 50 for WLTC and test 33 for SRC). AT values for different reference temperatures can be found in Table 7.

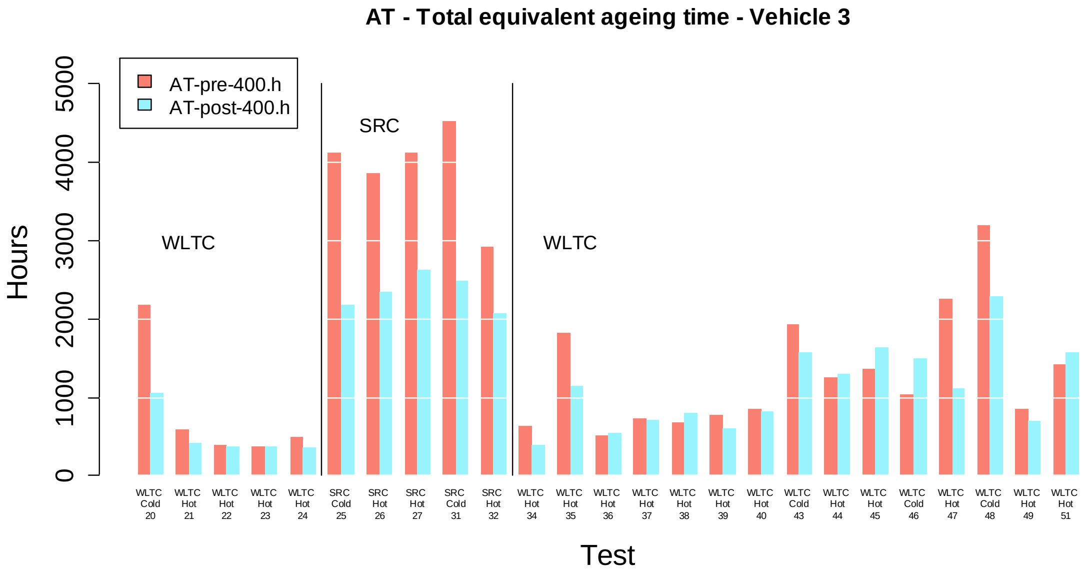


Source: JRC



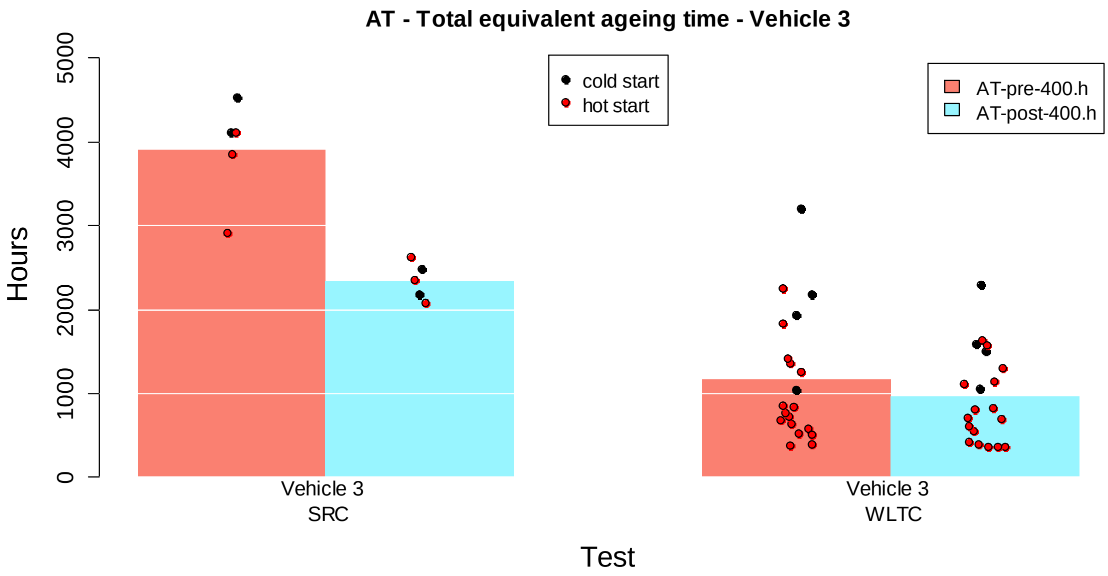
Source: JRC

Figure 29. Sequence of total equivalent ageing time, AT, for WLTC and SRC tests, excluding those with regeneration of the diesel particle filter.



Source: JRC

Figure 30. Summary of total equivalent ageing time, AT, for WLTC and SRC tests without DPF regeneration. Bar plots represent the average values and data points are the single cold (black) and hot (red) start tests.



Source: JRC

3.4 Vehicle 4

The technical specifications of vehicle 4, extracted from Table 1, are presented in Table 8. This compressed ignition passenger car was equipped with diesel oxidation catalyst for the oxidation of hydrocarbons and carbon monoxide, a selective catalytic reduction (SCR) system for NOx reduction and a DPF for particle mass reduction. A first thermocouple (pre-cat) was installed at engine-out, before the after-treatment system. A second thermocouple (post-cat) was installed under the vehicle floor after the after-treatment system; see Figure 31. 41x WLTC and 11x SRC cycles were run following the test matrix in Table 9 without major violations, as can be seen in Figure 32 which reports overlapped speed profiles for all tests.

Temperature profiles, in particular post-cat temperatures in Figure 33 and Figure 34 were used to identify the tests in which the active regeneration of the DPF took place. The DPF regenerated during WLTC test 89 in the medium and high speed phases, during SRC tests 100, when regeneration started at about t = 1600 sec, and during test 101 which was run right after 100 to allow for complete DPF regeneration. In both WLTC and SRC test types the DPF regeneration lasted about 800 sec as can be seen in Figure 35 obtained after combining tests 100 and 101. PN measurements for test 100 are shown in Figure 36 confirming the DPF regeneration started at the end of the test.

Reference temperatures T = 400, 700, and 800 °C, in the range of the pre-cat and post-cat temperature profiles, and thermal reactivity R = 11 550, prescribed for the SCR based on Cu-Ze (copper-zeolite) by the EU legislation (see for instance Regulation (EU) 2016/1718) were chosen for the calculations of the total equivalent ageing time (AT) based on the methodology described in section 2.2 and reported in Table 9. AT values are displayed in Figure 37 (upper panel for WLTC and lower panel for SRC) indicating, similar to vehicle 3, a large sensitivity with respect to the reference temperature, with AT spanning 3 orders of magnitude for T_{ref} in the range 400-800 °C. It is again clear that the thermal load related to tests with DPF regeneration is much larger than in tests without DPF regeneration: 110 times and 140 times larger for WLTC pre-cat and post-cat temperatures respectively; 10 times larger for SRC pre-cat and post-cat temperatures. In addition, as summarized in Figure 38 and Figure 39 with all tests without DPF regenerations, the AT from SRC tests is larger than the AT from WLTC cycles. A p-value << 0.05 from a statistical t-test with 95% confidence level confirmed that the two groups (WLTC and SRC) were different, with AT(SRC) about two times AT(WLTC) as displayed in Figure 39. Note also the smaller dispersion of data points around the average value in Figure 39 in comparison with the same type of results for vehicle 3 in Figure 30 due to the absence of random temperature peaks during tests on vehicle 4. The coefficient of variation is now about 7% for vehicle 4 and T_{ref} = 400 C compared to 60% for vehicle 3.

The chosen thermal reactivity R = 11 550 is prescribed for the SCR based on Cu-Ze (copper-zeolite) by the EU legislation (see for instance Regulation (EU) 2016/1718). As we did not have access to the different components of the ATS separately, we have first chosen R1 = 11 550 and then reanalysed the data with R2 = 5 175, prescribed for Fe-Ze SCR systems, and R3 = 18 050 suitable for diesel oxidation catalysts. The results of these calculations are shown in Figure 40 confirming that qualitatively the discussion above remains valid: AT(SRC) remains larger than AT(WLTC) with the ratio AT(SRC)/AT(WLTC) proportional to the chosen thermal reactivity, from ratio = 1.5 for R2 to ratio = 2.3 for R3.

We observed an average mileage between regenerations of about 800-1000 km, confirmed by our records including tests performed for other measurement campaigns, meaning that during the useful life of the vehicle (160 000 km) the DPF of vehicle 4 (and downstream components of the ATS) would experience about 170 regeneration events. Compared to the 700 regeneration events of vehicle 3, vehicle 4 would be subject to about one fourth of the thermal load caused by DPF regenerations.

Table 8. Technical specifications of vehicle 4.

Vehicle	Vehicle 1
Engine type	CI
Injection	DI
After-treatment	DOC, SCR, DPF
EURO	EURO 6b
Fuel	B7
Displacement [cm3]	1560
Cylinders	4
Power [kW]	73
Transmission	MT
Gears	5
Mileage [km]	2950
Mass [kg]	1309
Year of registration	2017

Source: JRC

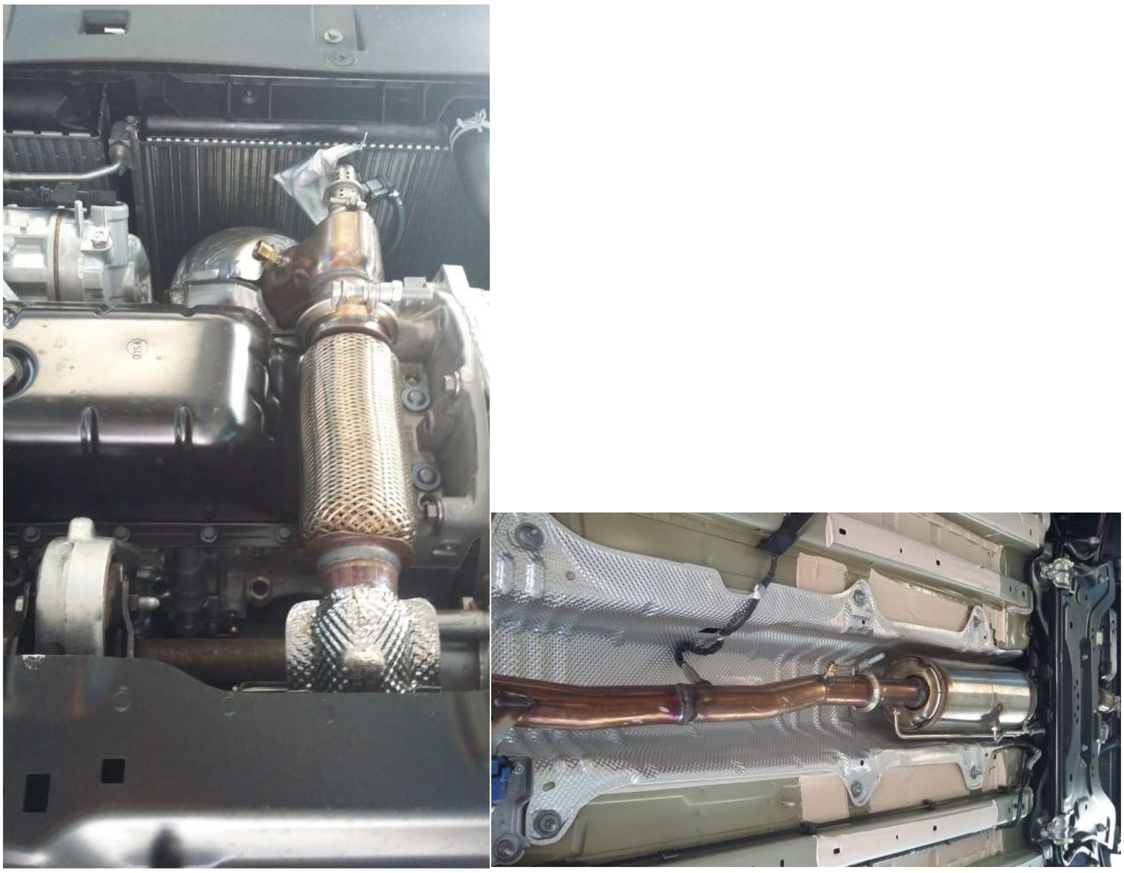
Table 9. Summary of test results for vehicle 4. The total ageing time (AT) is calculated for reference temperatures of 400, 700 and 800 °C.

Test No.	Vehicle	Driving Cycle	Cycle start	T Oil at t=0 [C]	Notes	AT-pre-400	AT-pre-700	AT-pre-800 [h]	AT-post-400	AT-post-700	AT-post-800
52	4	WLTC	Cold	34.65	1st cold	2291.1	11.6	3.8	121.9	0.6	0.2
53	4	WLTC	Hot	64.13	1st hot	1985.2	10.0	3.3	91.9	0.5	0.2
54	4	WLTC	Cold	21.48	2nd cold	2211.9	11.2	3.7	93.3	0.5	0.2
55	4	WLTC	Hot	94.32	2nd hot	1948.6	9.8	3.3	82.0	0.4	0.1
56	4	WLTC	Cold	17.37	3rd cold	2297.2	11.6	3.8	96.7	0.5	0.2
57	4	WLTC	Hot	98.13	3rd hot	2260.2	11.4	3.8	94.0	0.5	0.2
58	4	WLTC	Cold	44.66	4th cold	2268.1	11.4	3.8	97.5	0.5	0.2
59	4	WLTC	Hot	96.22	4th hot	2219.7	11.2	3.7	92.8	0.5	0.2
60	4	WLTC	Hot	73.495	5th hot	2117.5	10.7	3.5	97.9	0.5	0.2
61	4	WLTC	Cold	14.87	5th cold	2050.4	10.3	3.4	77.9	0.4	0.1
62	4	WLTC	Cold	21.13	6th cold	2110.7	10.6	3.5	91.4	0.5	0.2
63	4	WLTC	Hot	107.84	6th hot	1787.7	9.0	3.0	84.5	0.4	0.1
64	4	WLTC	Hot	72.09	7th hot	2322.0	11.7	3.9	97.9	0.5	0.2
65	4	WLTC	Cold	42.05	7th cold	2187.7	11.0	3.7	88.2	0.4	0.1
66	4	WLTC	Hot	87.01	8th hot	1883.3	9.5	3.1	79.9	0.4	0.1
67	4	WLTC	Hot	101.23	9th hot	1932.2	9.7	3.2	81.9	0.4	0.1
68	4	WLTC	Cold	21.33	8th cold	2095.0	10.6	3.5	80.1	0.4	0.1
69	4	WLTC	Hot	104.84	10th hot	2007.5	10.1	3.4	85.7	0.4	0.1
70	4	WLTC	Hot	86.21	11th hot	2070.7	10.4	3.5	86.7	0.4	0.1
71	4	WLTC	Cold	40.65	9th cold	1931.9	9.7	3.2	88.6	0.4	0.1
72	4	WLTC	Cold	20.03	10th cold	2075.9	10.5	3.5	92.3	0.5	0.2
73	4	WLTC	Hot	75.9	10th hot	1924.7	9.7	3.2	78.3	0.4	0.1
74	4	WLTC	Hot	106.44	11th hot	2143.2	10.8	3.6	106.8	0.5	0.2
75	4	WLTC	Cold	24.63	11th cold	2217.7	11.2	3.7	79.3	0.4	0.1
76	4	WLTC	Hot	108.74	12th hot	1923.4	9.7	3.2	83.9	0.4	0.1
77	4	WLTC	Hot	111.64	13th hot	1867.9	9.4	3.1	101.0	0.5	0.2
78	4	WLTC	Hot	110.24	14th hot	1913.4	9.7	3.2	103.4	0.5	0.2
79	4	WLTC	Cold	41.05	12th cold	1996.3	10.1	3.3	95.5	0.5	0.2
80	4	WLTC	Hot	108.34	15th hot	2057.2	10.4	3.4	102.8	0.5	0.2
81	4	WLTC	Hot	105.235	16th hot	2348.5	11.8	3.9	98.4	0.5	0.2
82	4	WLTC	Cold	20.93	13th cold	2166.0	10.9	3.6	101.8	0.5	0.2
83	4	WLTC	Hot	106.74	17th hot	1897.0	9.6	3.2	94.1	0.5	0.2
84	4	WLTC	Hot	107.64	18th hot	1994.2	10.1	3.3	111.4	0.6	0.2
85	4	WLTC	Hot	110.04	19th hot	2047.1	10.3	3.4	114.5	0.6	0.2
87	4	WLTC	Hot	108.44	20th hot	1957.1	9.9	3.3	105.9	0.5	0.2
88	4	WLTC	Cold	35.85	14th cold	2114.5	10.7	3.5	92.7	0.5	0.2

89	4	WLTC	Cold	30.3	15th cold	232959.5	1175.2	388.8	13537.3	68.3	22.6
90	4	SRC	Cold	NA	1st cold	4119.6	20.8	6.9	293.9	1.5	0.5
91	4	SRC	Hot	NA	1st hot	4144.5	20.9	6.9	314.6	1.6	0.5
92	4	SRC	Cold	20.23	2nd cold	3948.2	19.9	6.6	294.6	1.5	0.5
93	4	SRC	Hot	57.98	2nd hot	4375.4	22.1	7.3	328.5	1.7	0.5
94	4	SRC	Cold	28.8	3rd cold	3966.6	20.0	6.6	280.8	1.4	0.5
96	4	SRC	Cold	33.9	4th cold	3761.9	19.0	6.3	NA	NA	NA
97	4	SRC	Cold	40.9	5th cold	4196.1	21.2	7.0	358.9	1.8	0.6
98	4	SRC	Hot	103.8	3rd hot	4115.7	20.8	6.9	302.2	1.5	0.5
99	4	SRC	Cold	23	6th cold	4138.5	20.9	6.9	303.1	1.5	0.5
100	4	SRC	Cold	28.9	7th cold	78921.1	398.1	131.7	6795.0	34.3	11.3
101	4	SRC	Hot	111.2	4th hot	17621.6	88.9	29.4	921.6	4.6	1.5
102	4	WLTC	Cold	25.73	16th cold	2018.6	10.2	3.4	94.2	0.5	0.2

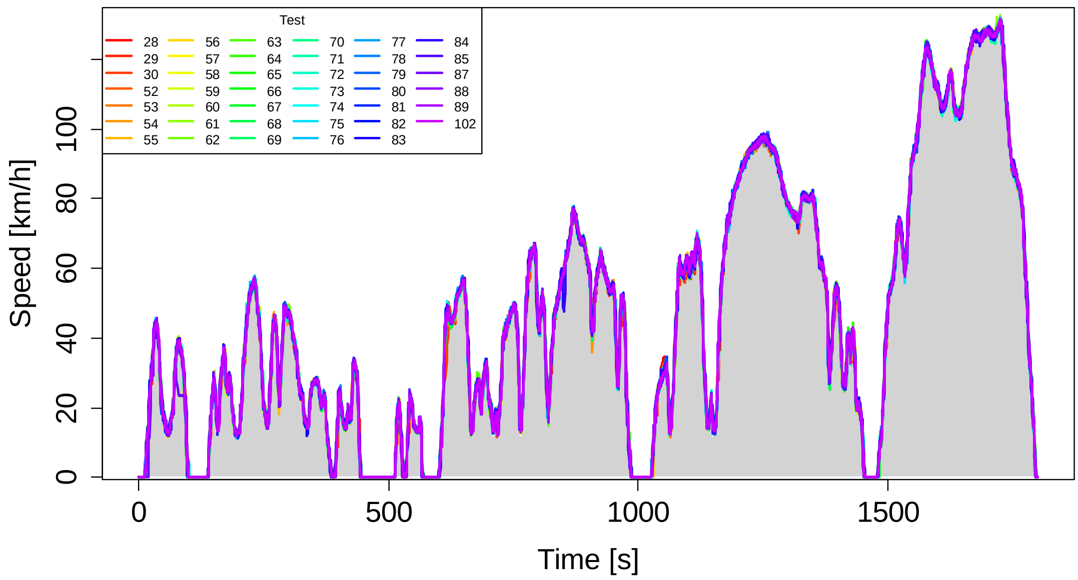
Source: JRC

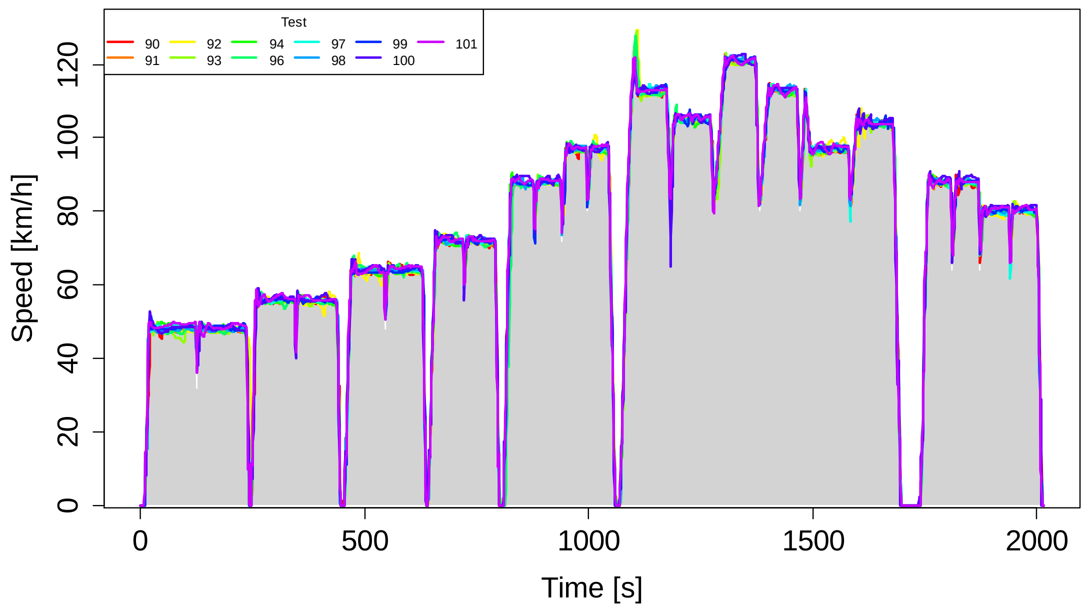
Figure 31. Installation of the pre-cat thermocouple close to the lambda sensor (left panel) and post-cat thermocouple under-floor (right panel) for the measurement of the temperatures before and after the after-treatment system.



Source: JRC

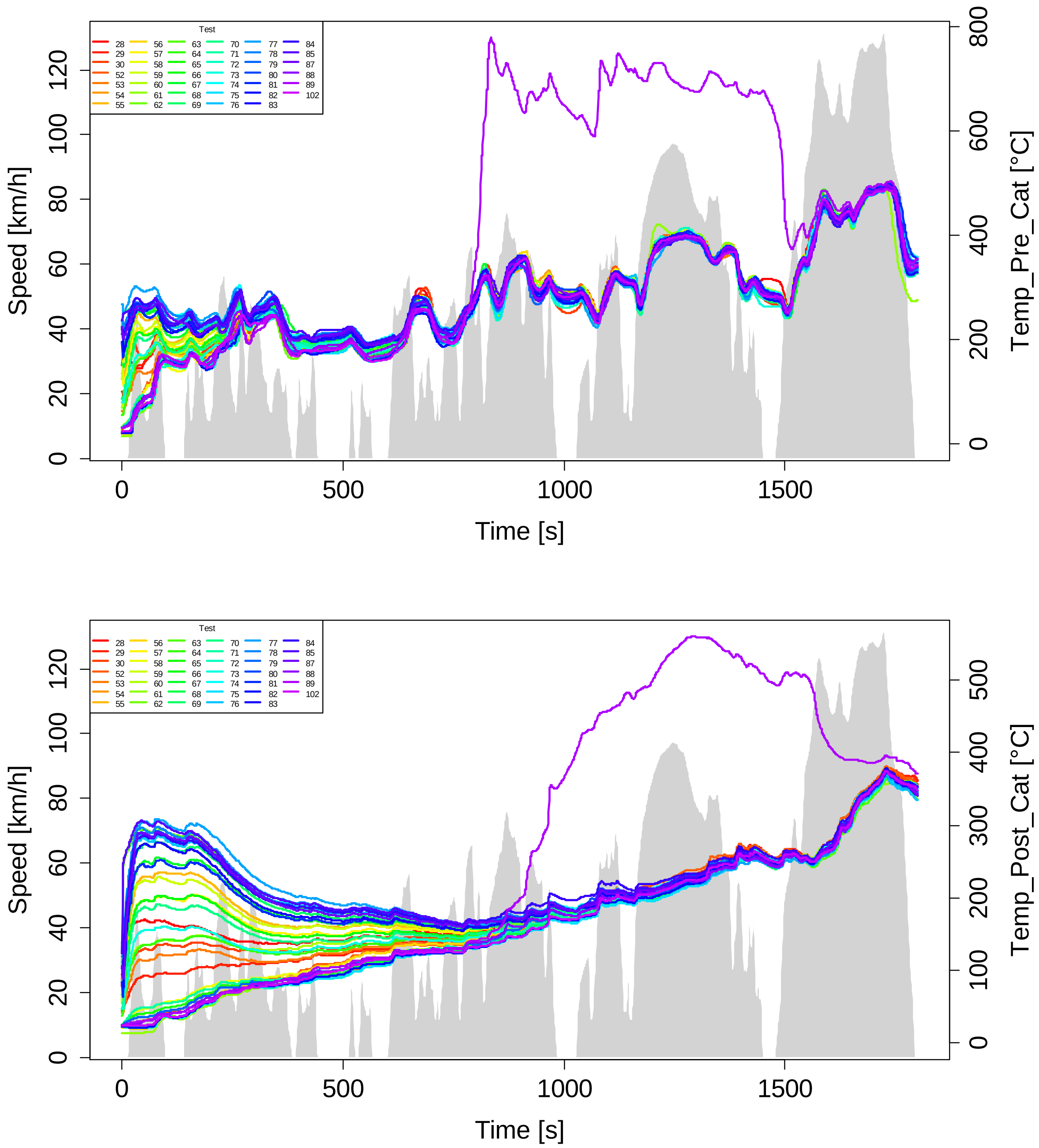
Figure 32. WLTC (upper panel) and SRC (lower panel) speed profiles for all tests on vehicle 4.





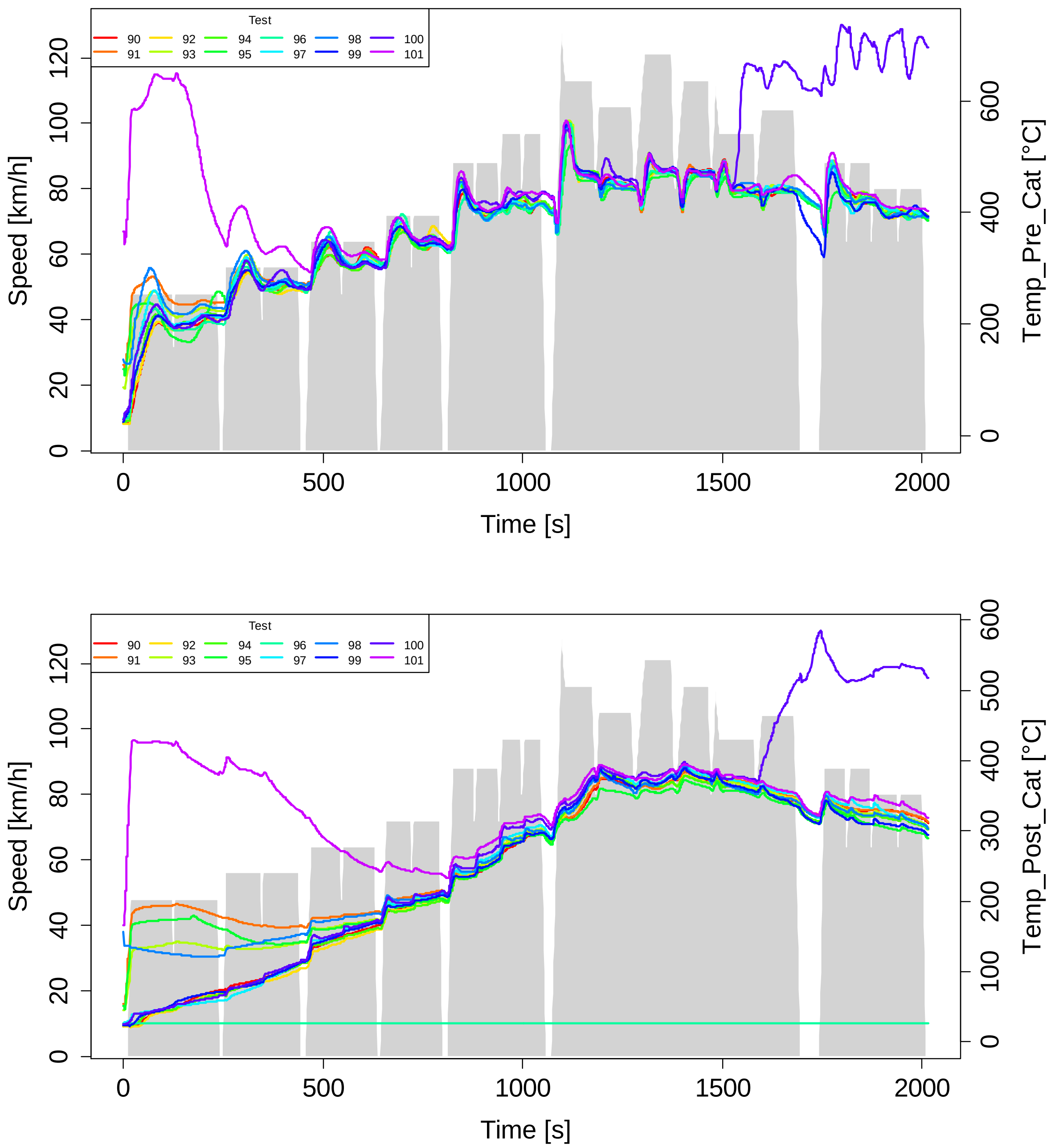
Source: JRC

Figure 33. Pre-cat (upper panel) and post-cat (lower panel) temperature profiles of WLTC tests on vehicle 4.



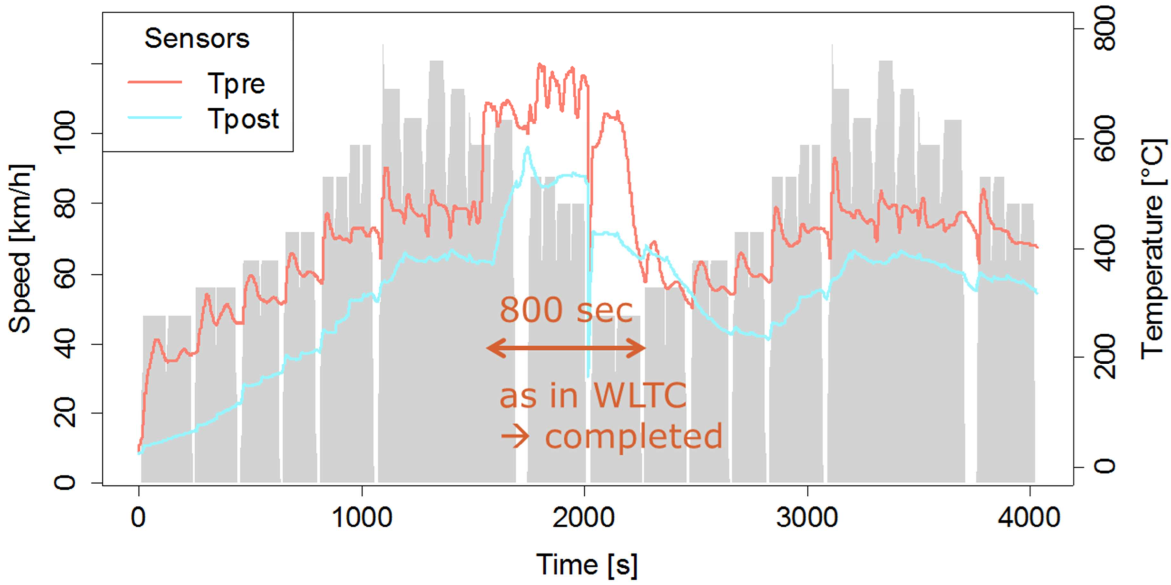
Source: JRC

Figure 34. Pre-cat (upper panel) and post-cat (lower panel) temperature profiles of SRC tests on vehicle 4.



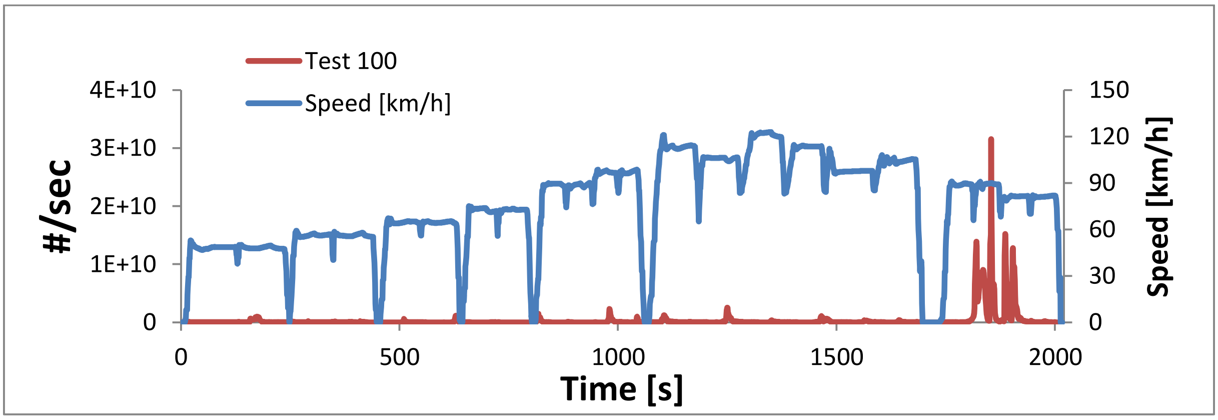
Source: JRC

Figure 35. Speed (grey shaded area) and temperature profiles of the combined test obtained by binding tests 101 and 102. The total regeneration time of about 800 sec is similar to that occurred during regeneration over the WLTC test 89.



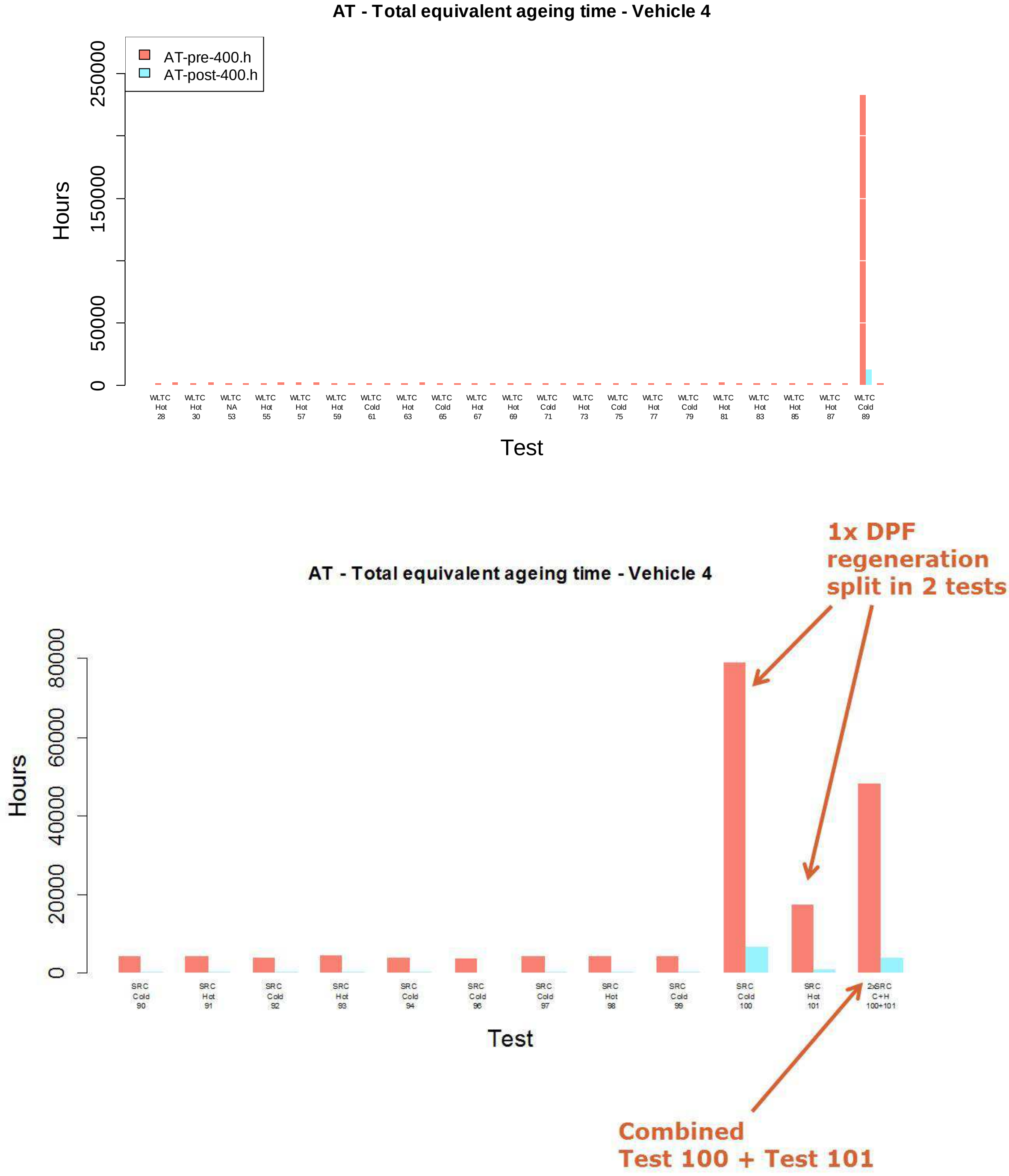
Source: JRC

Figure 36. Particle number measurements (# of particles per second) for test 100 with DPF regeneration starting at about 1700 sec.



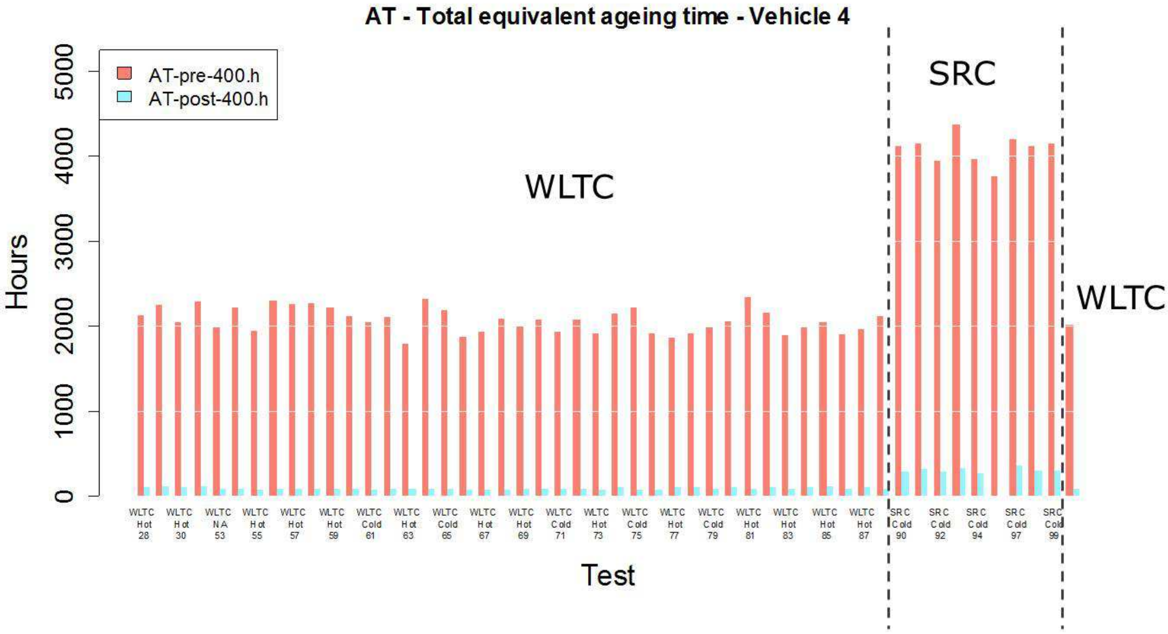
Source: JRC

Figure 37. Per-test equivalent ageing time (hours) for pre-cat and post-cat temperatures with reference temperature T_{ref} = 400 °C: WLTC tests in the upper panel, SRC tests in the lower panel. The largest values are related to tests where regeneration took place (tests number 89 for WLTC and tests 100 and 101 for SRC). Tests 100 and 101 were combined and AT recalculated.



Source: JRC

Figure 38. Sequence of total equivalent ageing time, AT, for WLTC and SRC tests, excluding those with regeneration of the diesel particle filter.



Source: JRC

Figure 39. Summary of total equivalent ageing time, AT, for WLTC and SRC tests excluding those with regeneration of the diesel particle filter. Reactivity R1 = 11550.

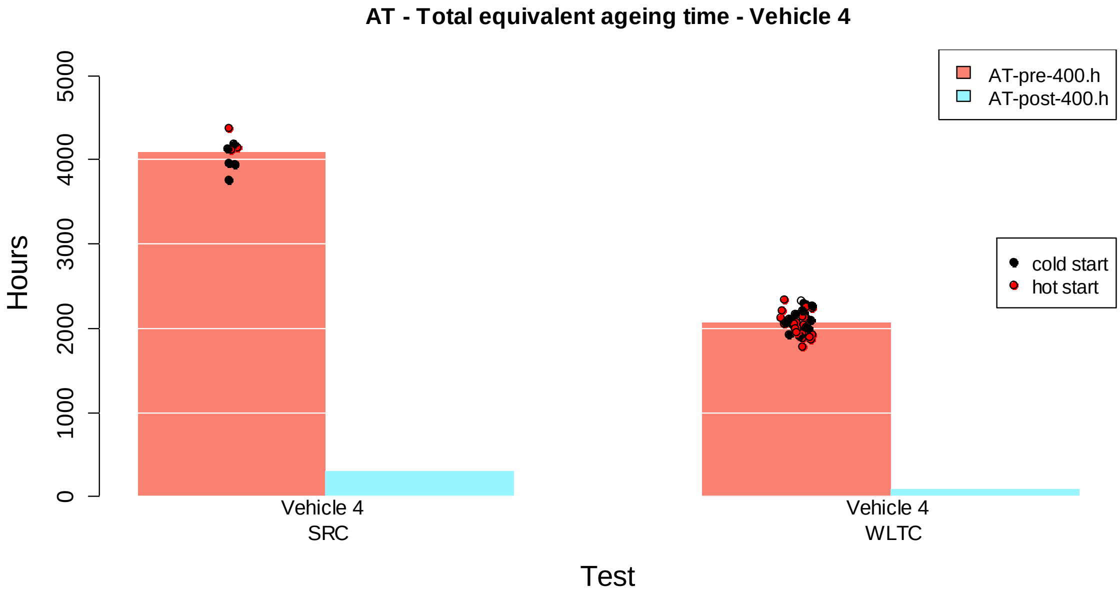
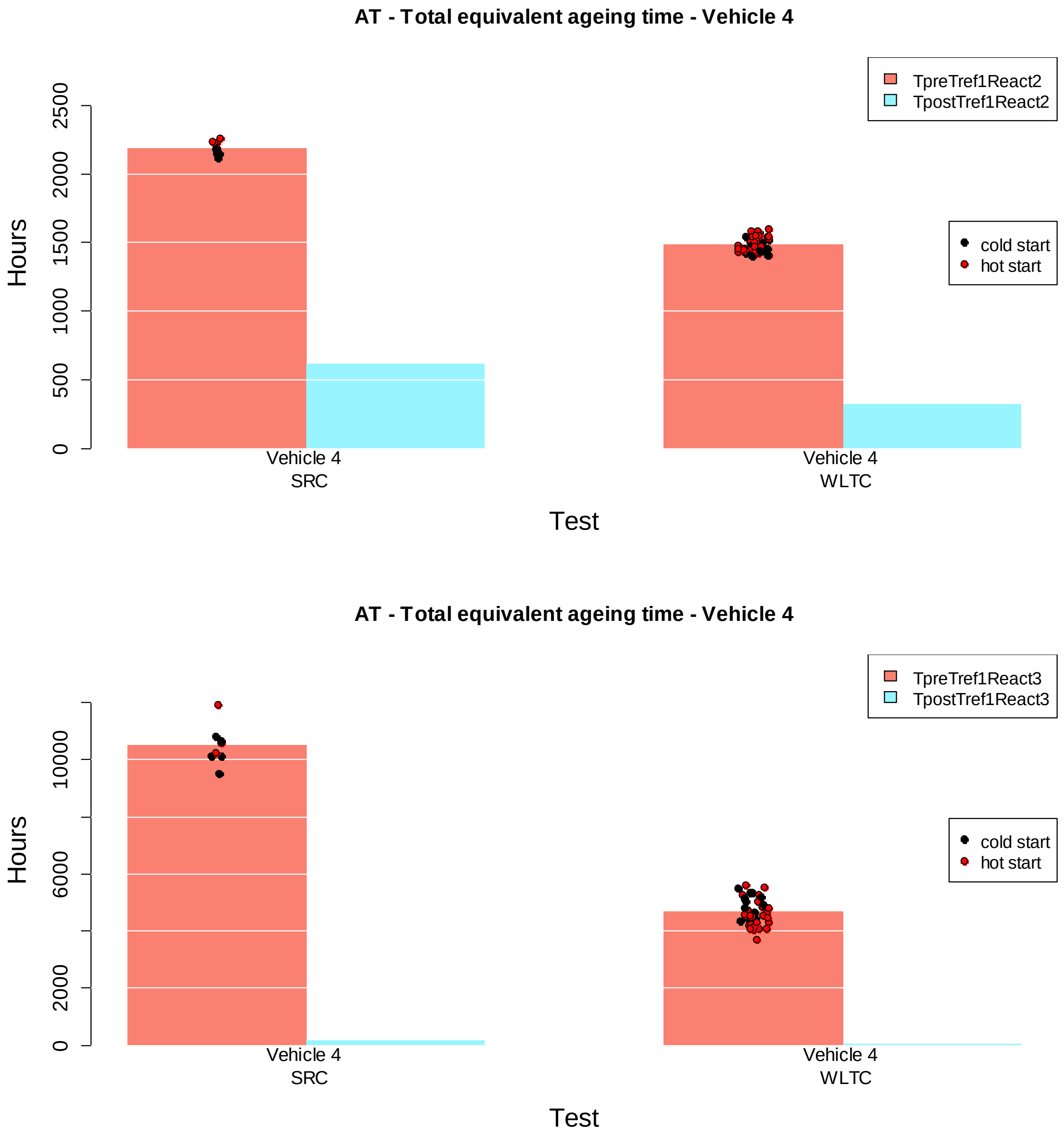


Figure 40. Summary of total equivalent ageing times in hours for T_{ref} = 400 °C , thermal reactivity R2 = 5 175 (upper panel) and R3= 18 050 (lower panel). DPF regenerations are not included.



Source: JRC

3.5 Aggregated results

In this section the results from the 4 test vehicles previously presented are summarized and compared.

Figure 41 shows the average pre-cat temperatures experienced by the vehicles during all WLTC and SRC tests. For each vehicle, SRC tests (circles) were clearly characterized by larger average temperatures than WLTCs (triangles). Similarly, the tests on vehicle 4 during which the DPF regeneration occurred (identified by the letter "R") exhibited larger average temperatures than corresponding WLTC or SRC tests without regeneration. Temperatures of vehicle 3 (equipped with LNT) were instead affected by frequent and random spikes not related to complete DPF regenerations (see section 3.3), and thus were characterized by generally lower discrepancy between regenerating and non-regenerating tests. As a consequence, the temperature ranges of vehicle 3 are constrained in a smaller range than vehicle 4.

Equivalent ageing time (AT) calculations which involved the non-linear dependence from temperature described in 2.2 are summarized in Table 10. Figure 42 shows the average AT of Table 10 for gasoline and diesel vehicles (upper and lower panel, respectively) including single test data points colour-coded based on the initial test conditions (cold/hot start) and excluding tests with DPF regeneration. Concerning the gasoline vehicles, the ranges of AT were similar when fixing the variable (pre-cat or post-cat temperature), and varying the test cycle type: similar thermal loads were experienced by the after-treatment system over the SRC and the WLTC test cycles for both vehicles. The magnitude of the thermal loads comparing the two gasoline vehicles were instead different, higher for vehicle 1 (equipped with a PFI system) than vehicle 2 (mounting a stoichiometric GDI engine) for both WLTC and SRC. In all tests, the post-cat temperatures were larger than pre-cat ones.

The opposite scenario emerged from the comparison of diesel vehicles. The ranges of AT overlapped for the 2 vehicles when considering the pre-cat temperature and fixing the test cycle type (SRC or WLTC): similar thermal loads were experienced by the after-treatment systems over the same test cycle as no statistical difference between the 2 groups based on 95% confidence level t-test was observed; see summary in Table 11. Post-cat temperatures were instead different: lower for vehicle 4 equipped with SCR than vehicle 3 equipped with LNT. In all tests, pre-cat temperatures were larger than post-cat ones. The same analysis reveals that for both diesel vehicles the thermal load over the SRC is higher than over the WLTC. The magnitude of this difference depends on the vehicle and on the chosen thermal reactivity as explained in section 3.4. In our study we found that for diesel vehicles the SRC was from 1.5 to 4 times more severe than the WLTC depending on the chosen sampled variable.

Test cycles with DPF regenerations were characterized by higher AT than in tests without DPF regenerations as can be seen in Figure 28 and Figure 37. The differences were more pronounced for post-cat than pre-cat temperatures due to exothermal reactions inside the after-treatment system. In addition, we observed dependence on both the vehicle and test cycle. Considering the pre-cat temperature, the SRC tests with DPF regenerations were from 3 times to 12 times more severe than non-regenerating ones. Larger differences characterized the WLTC tests with and without DPF regenerations: from 20 to 110 times more severe when the regeneration occurred.

The 2 diesel vehicles deployed different DPF regeneration strategies. We calculated the average mileage between two regenerations: about 200 km for vehicle 3 and about 800-1000 km for vehicle 4. This means that during the useful life (160 000 km in the Euro 6 legislation) the thermal load of vehicle 3 included about 800 DPF regenerations, while they were about 180 for vehicle 4. It is interesting to compare the contribution to thermal load from the tests with DPF regenerations with the contribution from tests covering the mileage between 2 DPF regenerations, over the useful life of the vehicle. Figure 43 shows the pie-charts of thermal load from regenerating and non-regenerating tests for vehicle 3 and vehicle 4. Very similar results from both test vehicles indicate that about ¾ of the thermal load experienced by the ATS during the useful life of the vehicle originated from DPF regenerations, while the remaining ¼ was related to the WLTC tests without regenerations. This proves that while the DPF regeneration is indeed the largest contributor to thermal load, the mileage driven without DPF regenerations cannot be neglected.

Figure 41. Average temperature experienced by the 4 vehicle during all WLTC and SRC tests.

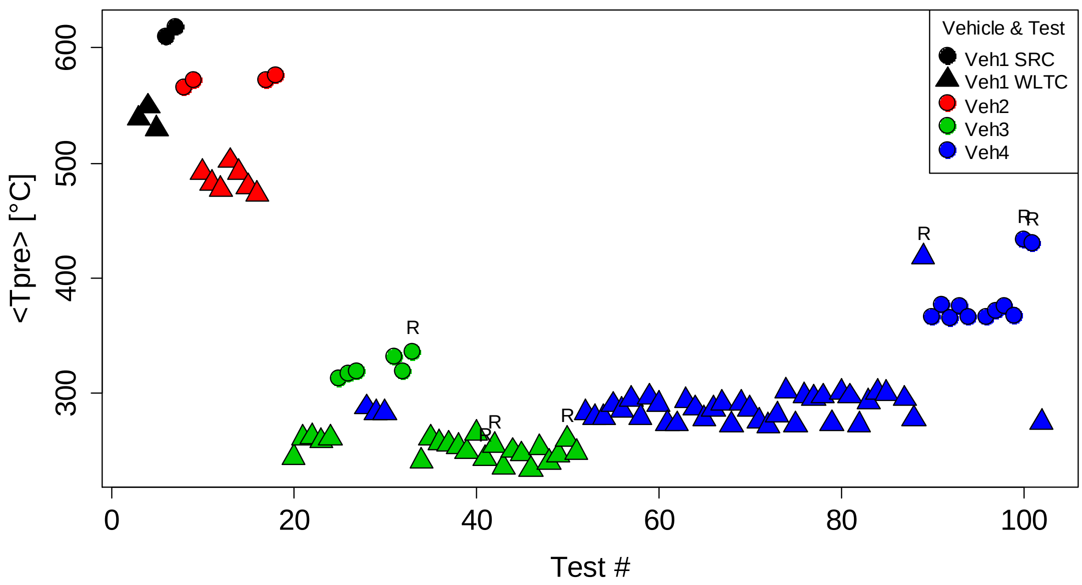
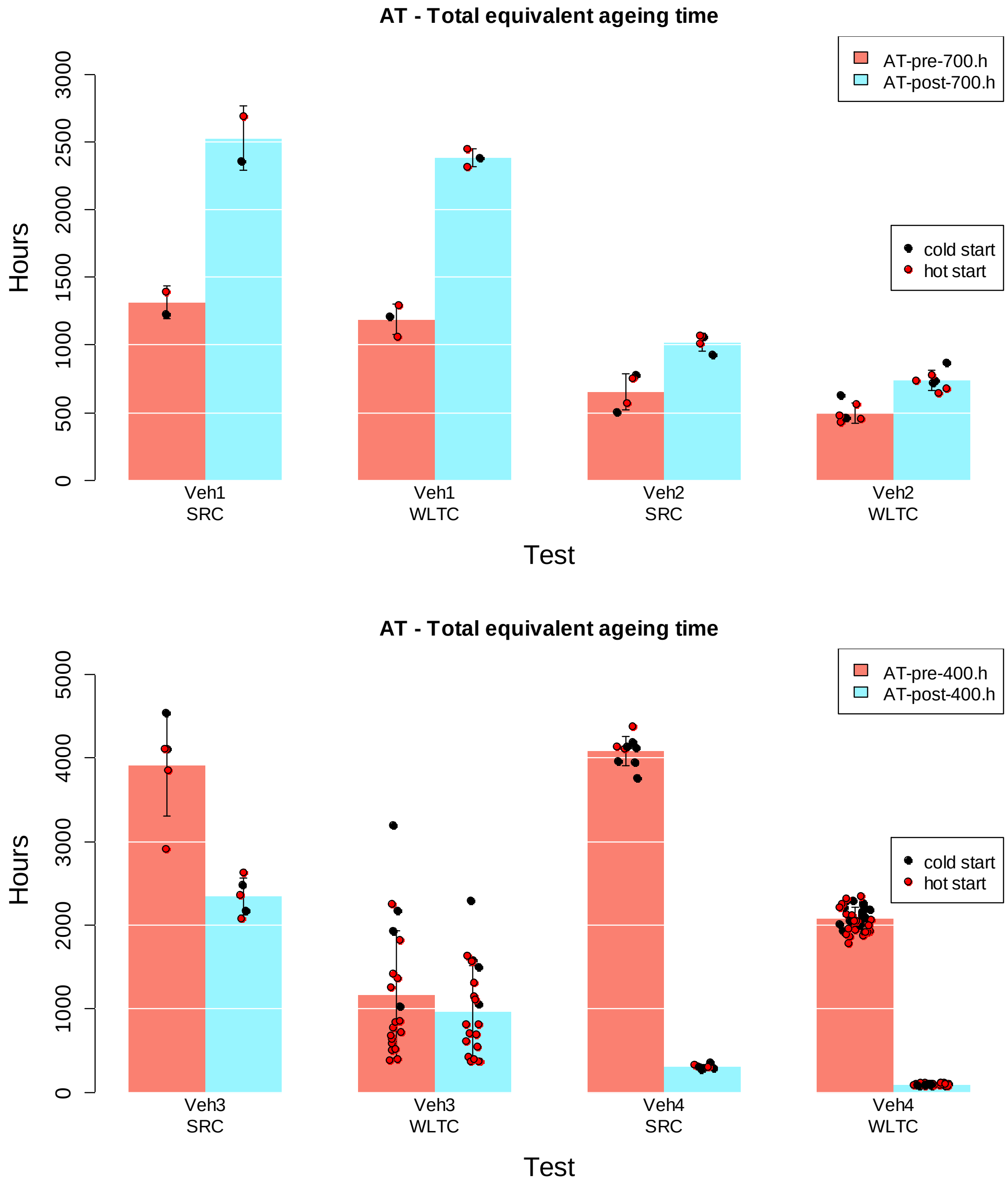
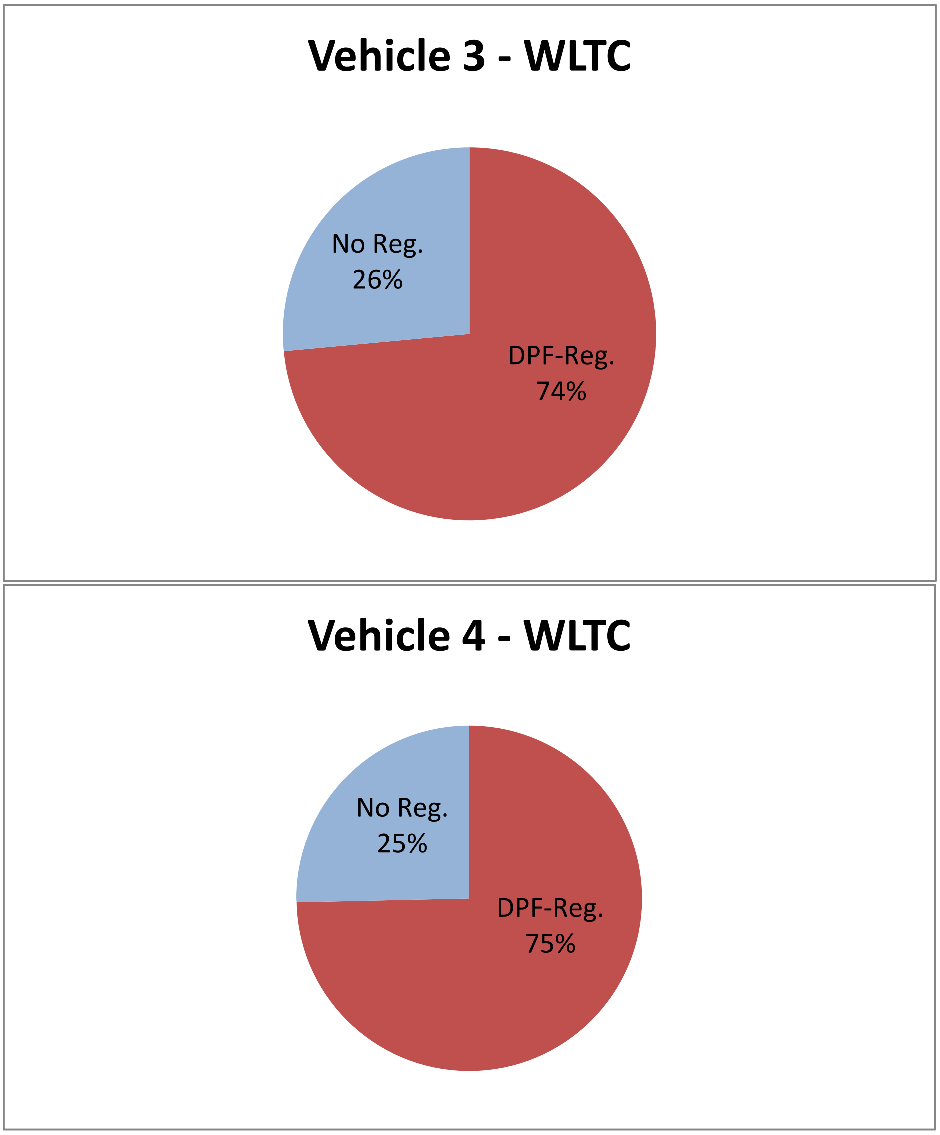


Figure 42. Averaged equivalent ageing time for the 2 test vehicles (bar plots) with overlapped single data points split between cold start and hot start tests. Tests with DPF regeneration were not included.



Source: JRC

Figure 43. Share of thermal load for WLTC tests with and without DPF regeneration. Values were rescaled to the useful life of the vehicle.



Source: JRC

Table 10. Summary of average equivalent ageing times (AT) for all vehicles broken down by test cycle (SRC or WLTC) and different thermal reactivities (vehicle 4). ATs were calculated from pre-cat and post-cat temperatures and for 3 different reference temperatures: 400, 700 and 800 °C. Tests with DPF regenerations were excluded.

Vehicle	Techno-logy	Cycle	Thermal Reactivity	AT-Pre 400	AT-Pre 700	AT-Pre 800	AT-Post 400	AT-Post 700	AT-Post 800
						[hours]			
1	SI, PFI	SRC	17 500	3.98E+06	1314	246	7.65E+06	2529	473
		WLTC	17 500	4.12E+06	1364	255	8.21E+06	2714	508
2	SI, GDI	SRC	17 500	1.97E+06	652	122	3.08E+06	1019	191
		WLTC	17 500	1.51E+06	498	93	2.23E+06	738	138
3	CI, LNT	SRC	18 050	3907	1.0	0.18	2343	0.6	0.1
		WLTC	18 050	1169	0.3	0.1	967	0.3	0.0
4	CI, SCR	SRC	11 550	4085	20.6	6.8	310	1.6	0.5
		WLTC	11 550	2077	10.5	3.5	95	0.5	0.2
		SRC	5 175	2191	205	124.8	617	57.6	35.1
		WLTC	5 175	1483	138.7	84.5	323	30.2	18.4
		SRC	18 050	10519	2.7	0.5	181	0.0	0.0
		WLTC	18 050	4674	1.2	0.2	45	0.0	0.0

Source: JRC

Table 11. Summary of 2-group t-test results with 95% confidence level performed on total equivalent ageing times calculated from both pre-cat and post-cat temperature variables. The reference temperature is not indicated, as it does not affect the t-test results. Tests with DPF regenerations were excluded.

Vehicle	Tech	N-SRC	N-WLTC	p-value	Response WLTC VS SRC
1	Gas	2	3	>0.05	Might be equal
2	Gas	4	7	>0.05	Might be equal
3	Diesel LNT	5	20	<< 0.05	Differ
4	Diesel SCR	9	40	<< 0.05	Differ

Source: JRC

4 Conclusions

The experimental activity started in April 2017 and finished in February 2018 with a total of 97 successful roller bench tests (WLTC and SRC) on 4 vehicles involving 3 technicians and 1 research scientist. Table 12 summarizes the experimental programme activity. The total number of tests does not include 8 pre-conditioning tests and 5 failed tests caused by unwanted stops of the vehicle, broken thermocouples or excessive speed profile violations.

Table 12. Summary of the completed test matrix.

Vehicle	**Veh 1 SI(1)**	**Veh 2 SI**	**Veh 3 CI(1)**	**Veh 4 CI**
WLTC tests	3	7	23	41
SRC tests	2	4	6	11
# of tests per vehicle	5	11	29	52
Total WLTCs	74			
Total SRCs	23			
Total tests	**97**			

(1) SI = spark-ignition; CI = compressed ignition

Source: JRC

We can conclude that:

— The thermal load related to SRC tests was statistically similar to that of WLTC for the 2 gasoline vehicles.

— For the 2 diesel vehicles the thermal load related to SRC tests was from 1.5 to about 4 times larger than that of WLTC, depending on the chosen sampled variable (pre-cat or post-cat temperatures) and input parameters (reference temperature and thermal reactivity of the anti-pollution systems).

— Repetitions of SRC tests can exhibit a large dispersion of thermal load results (as measured from the exhaust gas temperature variations) even in the case of identical speed traces (within the allowed speed tolerance) and this is mainly due to the different driving styles and gear-shift strategies applied arbitrarily by the driver in absence of specific legislation provisions. Note that we measured the temperature of the gas and not the temperature of the substrate of the catalyst.

— The SRC test to be performed in type-approval Test V could probably benefit in terms of repeatability from the introduction of an agreed gear-shift strategy and driving instructions

— WLTC and SRC tests during which the regeneration of the diesel particle filter occurred were characterized by dramatically larger thermal loads than in tests without diesel particle filter regeneration.

— The regeneration frequency of the diesel particle filter may be considerably different for different passenger car models. We found a mileage between 2 DPF regenerations equal to about 200 km for vehicle 3 and about 900 km for vehicle 4 meaning that vehicle 3 and vehicle 4 would experience about 800 and 180 regeneration events, respectively, during their useful life (160 000 km).

— The analysis of the contribution to total thermal load from WLTC test without DPF regeneration and from tests when the regeneration occurred indicated that during the useful life of the vehicle 25% of the thermal load was related to mileage driven in between 2 regeneration events.

Given the results above, we can conclude that the SRC test is appropriate for the aging of anti-pollution devices as defined in the Type V test.

In addition, we note the following:

— The temperature profiles of tests on vehicle 3 were characterized by several temperature peaks lasting about 1 minute and probably linked to the regeneration of the lean-NOx trap. Whatever their cause, those peaks strongly affect the thermal load and are responsible of the dispersion of equivalent ageing time results around the average value.

— The evaluation of a driving cycle based on the temperature profiles could enormously benefit from available OBD information such as intermediate temperature acquisitions at each stage of the after-treatment block and consistent information on the DPF regeneration.

— The present study has the limitation of not considering the temperature profiles in between pre-cat and post-cat temperatures which were taken before and after the entire after-treatment block. A related study commissioned by DG-GROWTH is on-going and will partially fill this gap.

5 Task 2: Literature survey on diesel vehicle ATS

The Durability Task Force of the Worldwide-harmonized Light duty vehicles Test Procedure group of the United Nations (WLTP-DTF, see section 1.2), chaired by the European Commission, established two sub-groups (a "diesel group" and a "gasoline group") with the task of collecting the available information about gasoline and diesel after-treatment systems (ATS) and diesel exhaust gas recirculation (EGR). The task related to diesel ATF and EGR corresponds to Action 3 of the work plan of the Durability Task Force described in section 1.2, with focus on the following subjects:

— Aging mechanisms causing deterioration of (existing and under development) ATS and their relative importance (e.g. thermal aging vs chemical poisoning vs mechanical stress).

— Methods used to simulate these deterioration effects in accelerated bench aging tests (e.g. chemical poisoning).

— Characteristics of the engine to be used for accelerated bench aging if not the same for which the ATS had been designed.

— The impact of exhaust flow rate on accelerated bench aging tests.

— Different EGR systems and their interaction with engine durability issues.

— Impact of different EGR rates on its durability and engine drivability.

The following discussion refers to the literature items listed in section 5.1. A similar task was undertaken in chapter 2 of the JRC Science for Policy Report No. JRC87070, which is propaedeutic to the present discussion.

There is general consensus that the main deterioration mechanism of Diesel Oxidation Catalysts (DOCs) is the thermal ageing, i.e., detrimental chemical-physical processes (like sintering and alteration of precious metals and washcoat) that increase the DOC light-off temperature and/or reduce the active surface of the catalyst needed to oxidize unburned hydrocarbons and carbon monoxide [1,2,3]. The chemical poisoning by sulfur, phosphorus and zinc generally play a minor role. The reduction of lubrication oil consumption in newer engines and the introduction of cleaner fuels reduced the impact of chemical ageing with respect to thermal ageing. The sulfur content in the EU fuel has been dramatically reduced in the last decades down to 10 mg/kg in reference diesel type B5 (Regulation EC 692/2008).

In order to accelerate the poisoning of a DOC due to the phosphorus contained in the lubrication oil, doped lube oil with artificially increased content of additives can either be blended with the diesel and pass in the combustion chamber through the injector, or be injected in the intake/exhaust manifold [4]. Poisoned and then regenerated DOCs indicate that the catalyst performance is susceptible to the presence of soot and lube-oil on the washcoat [4]. Other approaches used modified burners instead of conventional combustion engines for ageing purposes. With this method, the rich and stoichiometric conditions of the exhaust flow can be better controlled with consequent faster production of heavily aged catalysts [5].

As pointed out by Ramanathan and Oh [6], the exhaust flow rate is an important parameter that affects the degree of accelerated catalyst aging: the larger the flow rate, the faster the thermal front propagation through the catalyst and the exposure to high-temperatures. Adjusting the flow rate will influence the homogeneity of ageing along the catalyst length. A comparison of different conditions including thermal and hydrothermal ageing, sulfation, typical DPF regenerated exhaust (high HC concentration), and normal diesel exhaust showed that the active regeneration (high HC concentration) is a slow ageing method compared to that obtained with an atmosphere with excess of oxygen (with or without water).

In general, the catalyst poisoning is dependent i) on the contaminating species such as sulfur, phosphorus and other fuel and oil additives, ii) on the recipe of precious metals used in a particular washcoat, and iii) on the exhaust flow rate. The equation used to calculate the total equivalent ageing time (see section 2.2.2) in UNECE Regulation 83 includes a multiplicative factor A = 1.1 (10% additive) which increases the catalyst ageing time to account for deterioration from sources other than thermal ageing of the catalyst. As far as the authors are aware, there are no recent literature items addressing a specific or common multiplicative factor to be included in that equation to compensate for catalyst poisoning.

Similar considerations as above can be applied to three-way catalysts, Selective Catalytic Reduction (SCR) systems for NOx abatement via additional urea injection and catalysed DPF. In the case of SCR, the thermal ageing of an upstream DOC may also lead to poisoning of the SCR with volatilized precious metals (e.g., Platinum). This in turn decreases the NOx-reducing performance of the SCR as more ammonia is oxidized due to the presence of additional catalytic compound [8].

In addition, the poisoning of catalysts is closely related to the ageing temperature as highlighted in Xuesen et al. [9] from both theoretical considerations and experimental activities on SCRs. Cold start conditions of the engines introduce additional complexity in the presence of unconverted light and heavy hydrocarbons depositing on the SCR and reducing its performance [10].

Even with the use of ultra-low sulfur diesel, sulfur poisoning can still be an issue especially for SCR catalysts [11]. Considering that temperatures in excess of 550 C can be harmful to the system, chemical deSOx methods have been tested on Cu-zeolite SCR by using low concentrations of reductants under net oxidizing conditions and thus by inducing a locally reducing environment on the catalyst surface. In general, Cu-Z and Fe-Z SCR are the preferred solutions due to their temperature tolerance and superior resistance to sulfur poisoning [12]. However, in actual use, the combination of thermal ageing and sulfur poisoning should be considered. As pointed out by Shan et al. [13], the regeneration of the DPF (and consequent high temperatures) is accompanied by SO_2 formation from substances accumulated on the DPF. These products pass through the SCR catalysts. Hence, the presence of SO_2 should be taken into account during the hydrothermal aging process for SCR catalysts. The presence of SO_2 can accelerate the destruction and result in irreversible collapse of the zeolite structure of SCR catalysts at high temperature. Chemical poisoning and hydrothermal ageing are strongly interrelated, but most of the studies treat them separately. Benramdhane et al. [14] studied the impact of laboratory thermal ageing and actual vehicle aging (over 80 000 km) on the structure and functionalities of a lean NOx-trap and concluded that both ageing processes were responsible for the reduction in NOx conversion, but due to different processes. In the case of vehicle ageing, the storage sites were poisoned by residual sulphur which also further decreases the number of available storage sites. Due to their lower price and sulfur tolerance, vanadium based SCR (V-SCR) have been extensively used and their chemical ageing mechanism studied in laboratory with accelerated methods, such as aerosol doping and impregnation. On the other hand, exposure to high temperature may lead to release of toxic vanadium species [15]. Liu et al. [16] collected field returned V-SCR systems from heavy duty trucks and reported zinc and phosphorus poisoning as main degradation: most of phosphorous was accumulated in the inlet position, while zinc distributed almost uniformly along the catalyst length.

Coupling LNT and SCR systems has been proposed in recent years as improved solutions for NOx abatement. Wang et al. [17] simulated the road ageing of LNT+SCR by thermal ageing, sulfur poisoning and alternated lean and rich cycling and concluded that the SCR can compensate the reduced NOx storage capacity of the LNT caused also by sulfur contamination. Similar conclusions where reached by Seo et al. [18] applying hydrothermal ageing and sulfur poisoning. In all cases sulfur poisoning can still be important especially when combined with dynamic thermal ageing.

An established technology to reduce NOx emissions of diesel engines is the Exhaust Gas Recirculation (EGR) system which recycles part of the exhaust in the engine inlet (typically in the range 0-50%) in order to decrease the in-cylinder combustion temperature. On the other side, the lower flame temperature worsens the car driveability (lower performance) and increases HC, CO and soot emissions which routed back in the combustion chamber have detrimental effects on engine durability [19, 20]. The soot increase accelerates the wearing of several engine parts, e.g. cylinder surfaces, rings, and valves as typical lubrication oil films are about 0.01 μm thick and soot particles can have larger diameters. In addition, chemical changes in oil composition and increased viscosity due to accumulation of soot and hydrocarbons may lead to engine wear through corrosion and oil additives depletion. At the same time, the EGR affects the size distribution of soot by increasing the particle number concentration in the accumulation mode and the particles of larger size [21]. At present, there is no knowledge of the effects of the dynamic size distribution changes of particulate matter on the anti-pollution systems installed downstream of the EGR.

Overall, we can conclude that a considerable amount of recent scientific publications on anti-pollution systems for automotive applications can be found in the literature. However, most of them treat specific cases of 1 contaminant affecting the performance of 1 anti-pollution device during a single specific ageing activity. In alternative, the studies deal with thermal ageing in combination with a specific type of poisoning on a single anti-pollution device. In practice, we face the situation in which a series of anti-pollution systems (typically for diesel passenger cars: DOC+SCR+DPF, or DOC+LNT+DPF) is affected by hydrothermal ageing in concomitance with poisoning over the entire useful life of the vehicle (160 000 km). Only 2 publications dealt with returned catalysts from real use which either belonged to heavy duty vehicles or were run for a limited mileage with respect to useful life. Extrapolating the information from the literature to fit the useful life ageing of a passenger car is not a safe scientific exercise. Nevertheless, useful indications point in the following directions:

— Catalysts' deterioration is certainly and largely influenced by hydrothermal ageing;
— Despite the use of cleaner fuels and lubricating oils, poisoning (by sulfur, phosphorus, alkali metals and other additives) is still a strong contributor to catalyst deactivation;
— Thermal ageing (especially if dynamic) and poisoning effects on anti-pollution systems should be studied and assessed together as the thermal conditions affect the degree of poisoning;
— The combination of LNT and SCR seems to be a promising solution for reducing NOx emissions from diesel engines;
— The combination of multiple anti-pollution systems, in additions to detailed, single device behaviour, should be investigated;
— The presence of an EGR certainly affects driveability and accelerates the engine and after-treatment systems degradation. While the driveability is dealt with by engine design and management, the effects of EGR on ATS during the entire useful life of a vehicle are at present not reported.

We recommend that more studies should focus on recent technology anti-pollution devices and their combined thermal and poisoning effects at least over the useful life of the vehicle and possibly beyond. In alternative, limited mileage studies should address the extrapolation of the results to the entire vehicle's useful life. Actual vehicle ageing on the roller bench should be separately performed via accelerated procedures based on the SRC driving cycle and other patterns similar to those of real-driving in order to assess the impact of dynamic thermal ageing.

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List of abbreviations and definitions

AMA	Approved Mileage Accumulation
AT	Total equivalent Ageing Time
CI	Compressed ignition
CO	Carbon monoxide
CO2	Carbon dioxide
DG-GROW	Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs
DF	Deterioration Factor
DOC	Diesel oxidation catalyst
DTF	Durability Task Force
EC	European Commission
HC	Hydrocarbons
IWG	Informal Working Group (in the United Nations context)
JRC	Joint Research Centre (of the European Commission)
LNT	Lean-NOx trap
NEDC	New European Driving Cycle
NOx	Oxides of Nitrogen
PM	Particle Mass
PMP	Particle Measurement Programme
PN	Particle Number
SI	Spark-ignition
SCR	Selective Catalytic Reduction
SRC	Standard Road Cycle
T_{ref}	Reference temperature for equivalent ageing time calculations
T_pre-cat	Temperature upstream of the after-treatment system
T_post-cat	Temperature downstream of the after-treatment system
THC	Total hydrocarbons
TWC	Three-way Catalyst
UNECE	United Nations Economic Commission for Europe
US-EPA	United States Environmental Protection Agency
VELA	Vehicles Emissions Laboratories (at JRC)
WLTC	Worldwide-harmonized Light duty vehicles Test Cycle
WLTP	Worldwide-harmonized Light duty vehicles Test Procedure

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KJ-NA-29278-EN-N

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doi:10.2760/510305

ISBN 978-92-79-88014-8