MODALES D3.1 Emission measurements

WORK PACKAGE	WP3: Impact of user behaviours
TASK 3.1	Real powertrain emission methodology and measurement
TASK 3.2	Brakes emission methodology and measurement
TASK 3.3	Tyre/Road emission methodology and measurement
TASK 3.4	Maintenance and tampering
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DISSEMINATION LEVEL	Public (PU)
STATUS	Final, approved by the European Commission
DUE DATE	31/05/2021
DOCUMENT DATE	11/10/2021
VERSION NUMBER	1.0

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 815189.

Quality control

	Name	Organisation	Date
Editor:	LAURIKKO, Juhani	VTT	17/05/2021
Peer review 1:	ALANKUS, Orhan	OKAN	04/10/2021
Peer review 2:	CHEN, Haibo	LEEDS	02/10/2021
Authorised by (Technical Coordinator):	LAURIKKO, Juhani	VTT	07/10/2021
Authorised by (Project Coordinator):	WINDER, Andrew	ERTICO	08/10/2021
Submitted by:	WINDER, Andrew	ERTICO	11/10/2021

Revision and history chart

Version	Date	Main author	Summary of changes
0.1	11/05/2021	J. LAURIKKO	Draft outline
0.2	18/05/2021	J. LAURIKKO	Contents for Tasks 3.1 and 3.4 added
0.3	18/06/2021	J. LAURIKKO	Contents for Tasks 3.2 and 3.3 added
0.4	08/07/2021	J. LAURIKKO	Updated contents of Ch.3
0.5	19/08/2021	J. LAURIKKO	Contents updated
0.6	28/09/2021	J. LAURIKKO	Contents updated
0.7	30/09/2021	J. LAURIKKO	Consolidated draft for peer-reviews
0.8	05/10/2021	J. LAURIKKO	Peer review comments partly addressed, waiting for updates on Ch. 3 and Ch. 4
0.9	08/10/2021	J. LAURIKKO	Peer review comments fully addressed. Submitted to Quality Manager, project and technical coordinators for authorisation
1.0	11/10/2021	A. WINDER	Final submitted version

Legal disclaimer

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List of abbreviations and acronyms

Abbreviation	Meaning
ARTEMIS Urban	Urban variant of the real-world driving cycles developed by ARTEMIS, a European project on the accuracy of emissions tests
CPC	Condensation particle counter
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
DSG	Direct-shift gearbox
EATS	Emissions after-treatment system(s)
EFM	Exhaust flow metering (a device, part of PEMS)
EGR	Exhaust gas recirculation
ELPI	Electric low-pressure impactor
EOBD	European On-board Diagnostics (system)
GPF	Gasoline particulate filter
GPS	Global Positioning System
HC	Total hydrocarbons
HEPA	High efficiency particulate air filter
NEDC	New European driving cycle
NOx	Nitrogen oxide
OBD	On-board diagnostics
PEMS	Portable emissions measurement system
PM	Particulate matter
PM_1	Particulate Matter 1 micrometre or less in diameter
PM_{10}	Particulate Matter 10 micrometres or less in diameter
$PM_{2.5}$	Particulate Matter 2.5 micrometres or less in diameter
PN	Particle number
PN_1	Particle Number 1 micrometre or less in diameter
PN_{10}	Particle Number 10 micrometres or less in diameter
$PN_{2.5}$	Particle Number 2.5 micrometres or less in diameter
PSD	Particle size distribution
RDE	Real-driving emissions (test)
TA	Type Approval
TWC	Three-way-catalyst
SCR	Selective catalytic reduction (of NOx)
WLTC	Worldwide harmonized light vehicles test cycle
WLTP	Worldwide harmonised light vehicle test procedure
WLTP-brake	Worldwide Harmonized Light-duty Vehicles Test Procedure for brake devices

Executive Summary

The MODALES project works towards reducing air pollution from all types of on-road vehicles by encouraging the adoption of low-emission driving behaviour and proper maintenance choices.

For the purpose of finding interdependencies between driving styles and various emissions (exhaust, brake particles and tyre wear particles) a wide array of experimental work was planned and executed. The main purpose of these tasks was to measure the amounts of emissions generated, and simultaneously, characterise the driving behaviour. The goal was to establish a connection and correlation between measurable driving parameters and amounts of emissions, to be used in developing the basis for low emissions driving. As a separate task, the influence of maintenance on exhaust emissions was also studied.

Each main emissions domain (tailpipe exhaust, brake wear, tyre wear) had its own partner in charge that was responsible for designing and executing the work, as well as preparing and reporting the results. For the tailpipe emissions the lead was VTT, for brake wear BREMB, and for tyre wear BRIDG and MICH joined their expertise. In the experiments, most up-to-date instruments and measurement apparatus were employed, as well as the latest standards, where applicable.

Based on the results of the experiments, the work can be considered to be successful, as in the experiments many different driving styles were captured, and significant variations in resulting emissions could be measured. This gave a good standpoint for developing the mathematical equations, based on the inter-dependencies of driving parameters and various species of emissions. However, this was accomplished by the fifth task of this work package, T3.5: Correlation of user behaviour variability with emissions. For this purpose, all the information of these experiments was conveyed in electronic format to LEEDS that was the main partner in charge of this work.

Those equations will be used in analysing driving behaviour and predicting the resulting emissions in WP6. They also form the core for developing the definition(s) of low-emissions driving (style) in WP5, and various different training and couching exercises shall be implemented to communicate that positive driving technique as widely as possible.

1. Introduction

1.1 Background of MODALES

The MODALES project works towards reducing air pollution from all types of on-road vehicles by encouraging the adoption of low-emission driving behaviour and proper maintenance choices.

MODALES pursues a user-centric approach to address all the challenges, which, on the one hand enhance low-emission practices, and on the other hand, suppress high-emission behaviour by researching, developing, and testing several innovative and complementary solutions in four key areas (driver, retrofits, EOBD and inspection) to reduce vehicle emissions from three main sources: powertrain, brakes and tyres.

The scope of vehicles covers all vehicle types, ranging from passenger cars to buses and trucks.

The main activities of MODALES are:

- Measurement of real-world vehicle emissions (exhaust, tyre and brake) and driving behaviour to produce accurate correlations between them using advanced mathematical and statistical techniques.
- Exploration of the most advanced technologies for retrofits designed to substantially reduce powertrain emissions from all types of vehicles and validate their effectiveness under different real-world traffic and environment conditions, and by various drivers.
- Undertaking an in-depth analysis of OBDs, periodic inspection and legal issues on tampering in Europe to help regulatory authorities put in place effective anti-tampering legislation, and help owners properly maintain their vehicles.
- Conducting extensive low-emission user trials (with both driving and maintenance practices), supported by awareness campaigns, to enhance public engagement and help drivers better understand the impact of their driving and maintenance behaviours in all situations.

1.2 Purpose and scope of this document

This document describes the work conducted in **Work Package 3: Impact of user behaviours**, and it summarises the results from tasks **T3.1: Real powertrain emission methodology and measurement, T3.2: Brakes emission methodology and measurement**, **T3.3: Tyre/Road emission methodology and measurement,** and task **T3.4: Maintenance and tampering**,

The main purpose of these tasks was to measure the amounts of emissions generated, and simultaneously characterise the driving behaviour, in order to establish a connection and correlation between measurable driving parameters and amounts of emissions, to be used in developing the basis for low emissions driving. As a separate task, the influence of maintenance on exhaust emissions was studied.

Apart from the summary of the results presented in this deliverable, a lot more information of all these experiments has been conveyed in electronic format to task **T3.5: Correlation of user behaviour variability with emissions**. That task is developing mathematical equations, based on the interdependencies of driving parameters and various species of emissions. Those equations will be used in analysing driving behaviour and predicting the resulting emissions. That part of Work Package 3 is reported in deliverable **D3.2: Correlation of user behaviour variability with emissions**.

1.3 Document structure

In the document each three tasks have their own main Chapters, where the methodology and contents of experimental work conducted is described in detail. Each of these chapters contains also a summary of the results obtained.

A common summary and conclusions chapter draws together the main findings and gives an outlook of how low-emissions driving could be characterised.

1.4 Scope and intended audience

Figure 1-1 below shows how this deliverable fits in the project and highlights related deliverables which will take into account the content of this one.

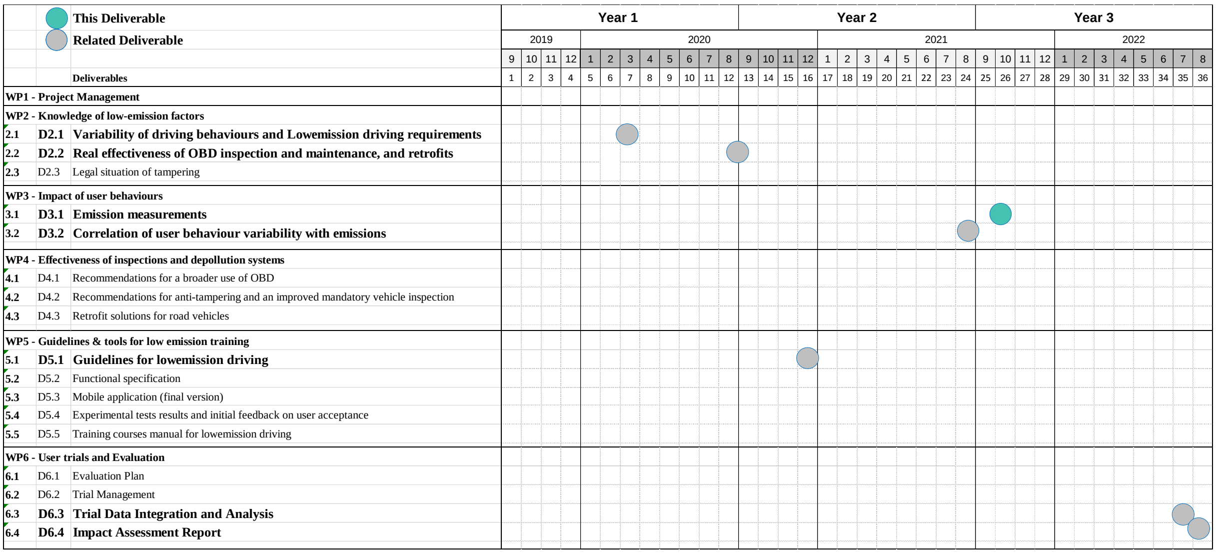


Figure 1-1: D3.1 Emission measurements, in the context of related MODALES deliverables

As a public deliverable, D3.1 is also of potential interest to an external audience concerned with both exhaust and non-exhaust emissions from all types of vehicles, but primarily of those powered by internal combustion engines.

1.5 Deviations from the Description of Action (DoA)

Regarding the contents of the work, no major deviations from the DoA were made. However, due to the COVID-19 pandemic, work was delayed in Task 3.1, as several different restrictions were imposed that hindered the progression of experimental work. Furthermore, in Task 3.3, the lock-downs drastically reduced driving. This delayed the execution of on-road tyre wear testing, as accumulation of kilometres plunged.

Regarding the execution of the experiments, the delay was some six months, which in turn delayed preparing this Deliverable that was due in M21 (end of May 2021), and it was submitted in the beginning of October 2021 (M26).

2. Real powertrain emission methodology and measurements

2.1 Purpose of the exercise

In this subtask, the influence of driver's driving style on exhaust emissions was studied.

2.2 Driver pool

For this purpose, a pool of drivers was recruited amongst the personnel of VTT in Espoo. Altogether 15 designated drivers were appointed, and some additional drivers were used to "fill the gaps", when a designated driver was not able to take the mission at the scheduled timeslot.

Of the designated drivers' pool, 10 were male and 5 were female. Their ages and years of driving experience is listed in Table 2.1. Due to the fact that VTT is an expert organisation with most of the employees having higher academic education, there are only a few young persons employed. Thus, we were not able to recruit very young, i.e. "rookie" type of drivers. Instead, half of the pool had 30 years or more of driving experience.

The drivers were allocated with a designator (an alphabet from A to O), and all data was labelled using these designators. The connection between the drivers' identity and this designator remained known only for a VTT crew member associated with this experiment. Furthermore, all subsequent use and analysis of the data did not even consider the characteristics of the drivers listed in Table 2.1, and the results were thus not in any way gender-specific.

Table 2.1: Break-down of the pool of test drivers

Age group, gender	Age [years]	Driving experience [years]	Age group, gender	Age [years]	Driving experience [years]
Young, male	30	12	Middle, female	39	21
Young, male	30	12	Middle, female	40	22
Middle, male	35	17	Middle, female	40	22
Middle, male	43	25	Middle, female	49	31
Middle, male	48	30	Middle, female	56	38
Middle, male	57	39			
Senior, male	60	42			
Senior, male	60	42			
Senior, male	62	44			
Senior, male	62	44			
Total, male	**10**		**Total, female**	**5**	**Total, both: 15**

2.3 Test route

For this exercise, a predefined route consisting of urban, rural and motorway sections was designed. It started from VTT's laboratory, where the test vehicles were prepared, and returned to the same place. For this reason, the first and the last 4.5 km were the same streets but driven to opposite directions. The goal was to choose the route that had different driving environments (street, road, motorway), and the traffic situation would not be too different depending on the day of the week or the hour of the day. Thus, the driver's individual driving style would be the significant feature and not the traffic around. Figure 2-1 depicts the route on a map.

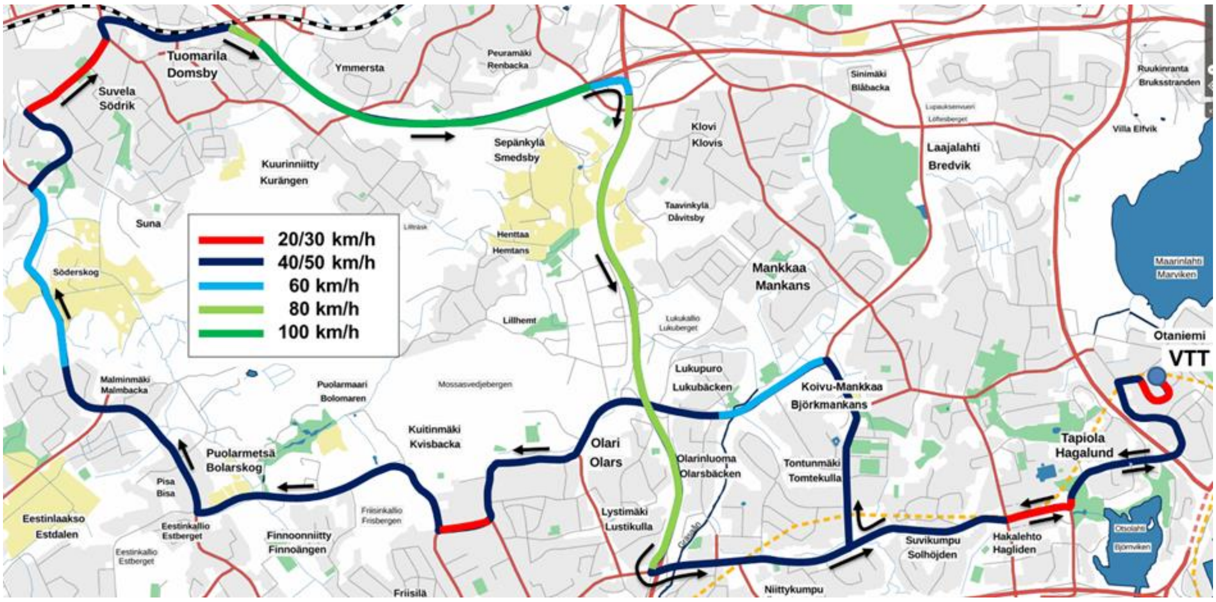


Figure 2-1: Test route schematics and speed limit sections

However, inevitably the route did have quite many features that would affect the driving, such as intersections, traffic lights and bus stops. The bus stops affect, because in these streets the speed limit was 60 km/h or below, and then the bus has priority, when leaving a bus stop. There were also some separate pedestrian crossings, apart from many in the intersections, and about half of those were raised to slow down the driving. Additionally, there were nine separate speed bumps, as well, for the same purpose.

Table 2.2 lists those features and the number of their occurrence. The number of actual stops in this table was based on one driver's driving that was recorded with an in-car camera to detect all the incidents occurring. In this example the number of actual stops recorded was 19, which is about 20% of all possible incidents (about 100) that could cause a stop. Therefore, we can say that at least for this example of driving, the traffic was quite fluid. However, no thorough statistical analysis of all tests was conducted.

Table 2.2: Test route break-down by features affecting to the driving

Type of feature	Intersections or similar	Traffic Lights	Bus Stops	Pedestrian Crossings	of which Raised	Speed Bumps	Actual Stops*
total	47	38	39	10	5	9	19

The total length of the route was about 31 km. Speed limits over the route differed from 40/50 km/h for most of the streets to short sections of 20 km/h in the very beginning and at the end, with a few short sections (2,4 km in total) of 30 km/h. The rural route sections of some 2.8 km had speed limit of 60 km/h. The motorway section (2.5 km) had 100 km/h speed limit, and the dual carriageway type of ring-road section (3.5 km) had speed limit of 80 km/h.

2.4 Test vehicles and fuels

Altogether six passenger cars were used as the test fleet. Of those, four were fuelled with petrol and two with diesel. Two were classified as small cars (category B), two were medium size (category C), and two were of the now popular cross-over type (category J), either as small (JS) or middle-sized (JM). We favoured manual transmissions, due to the fact that it reveals more of the driver's driving style, but two automated transmissions were also included, as those are gaining popularity amongst new passenger car registrations.

The petrol-fuelled cars were all with direct-injection engines, and all had the typical three-way catalyst (TWC) for controlling the gaseous emissions. Furthermore, two had also a particulate filter (GPF) to cut down the number of particulates. Both diesel cars were equipped with a combination of an SCR catalyst and a DPF.

Normal commercial fuels (petrol, diesel) were used in all tests.

Table 2.3. Lists some main characteristics of the test cars.

Table 2.3: Main characteristics of the test cars in PEMS tests

Car #	R1	R2	R3	R4	R5	R6
Make	Ford	Skoda	Skoda	Opel	Opel	Nissan
Model	Fiesta	Octavia	Octavia	Crossland-X	Corsa	Qashqai
Model Year	2015	2019	2017	2019	2021	2019
Size Category	B	C	C	JS	B	JM
Fuel	petrol	diesel	petrol	petrol	petrol	diesel
Engine (dm^3)	0.998	1.598	1.498	1.119	1.119	1.461
Induction	turbo	turbo	turbo	turbo	turbo	turbo
Power (kW)	73.5	85	110	81	77	85
Transmission	M5	DSG7	M6	A6	M5	M6
Mass (kg)	1130	1556	1470	1278	1055	1460
Euro Class	Euro 6a	Euro $6d_{\_temp}$	Euro 6c	Euro $6d_{\_temp}$	Euro $6d_{\_ISC\_FCM}$	Euro $6d_{\_temp}$
EATS	TWC	EGR+SCR/ DOC, DPF	TWC	TWC, GPF	TWC, GPF	EGR+SCR/DOC, DPF

2.5 Test equipment

A standard commercial PEMS device (AVL M.O.V.E.) was used to analyse and record exhaust emissions. In addition, a GPS system was used to record the momentary position (X, Y and Z coordinates) with 0.5 Hz time resolution, along with several parameters available via the EOBD-port of the cars. AVL Concerto software was used to process the recorded datafiles, and to produce output files.

The output file contains momentary (mg/s) and cumulative (g/test, g/km) values for the following species: CO, CO_2, NO, NO_2, NOx, PN (particulate number), as well as engine power (kW), torque (in % of max and Nm), speed (rpm), intake air pressure (kPa) and temperature (°C), coolant temperature (°C), exhaust temperature (°C, in the exhaust flow meter, EFM). The momentary vehicles speed (km/h) is available as from the vehicle of based or from the change in GPS position. The GPS positioning also gave the road inclination (gradient, %), as well as cumulative driven distance (km). In addition, ambient temperature (°C), pressure (kPa) and humidity (%) were recorded and included in the file.

Figures 2-2 to 2-7 depict the PEMS installations in the respective test cars. For the first three cars the installation was made using the towing hook and a subframe that allows the whole set to be placed outside the vehicle. Moreover, with the latter three, there was no towing hook, and then the analyser modules were installed inside the car in the boot or back set, with the smallest of the lot. Only the EFM that measures exhaust flow remains always out, as an extension to the tailpipe.

Figure 2-2: PEMS system installation on test car R1, Ford Fiesta

Figure 2-3: PEMS system installation on test car R2, Skoda Octavia 1.6 TDI

Figure 2-4: PEMS system installation on test car R3, Skoda Octavia 1.5 TSI

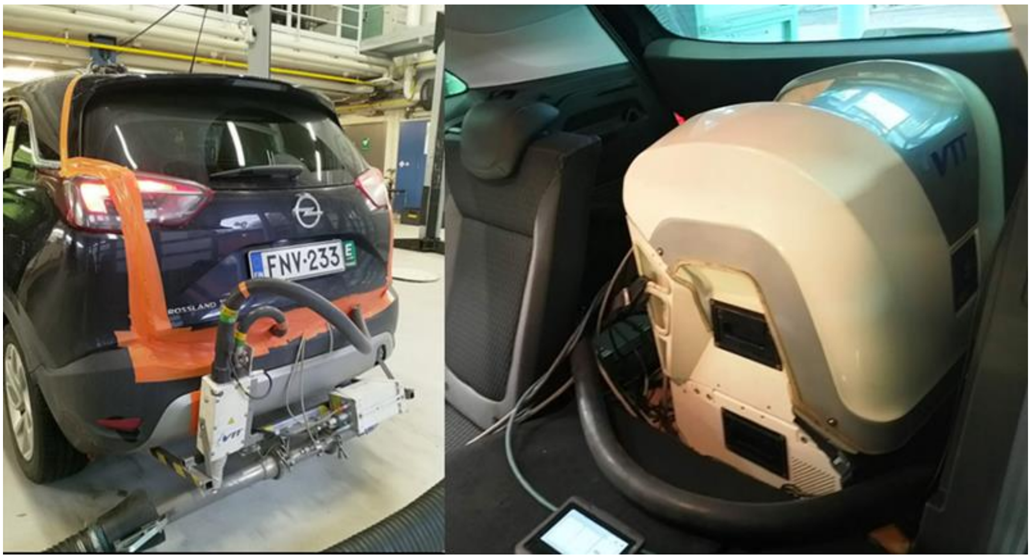


Figure 2-5: PEMS system installation on test car R4, Opel Crossland-X

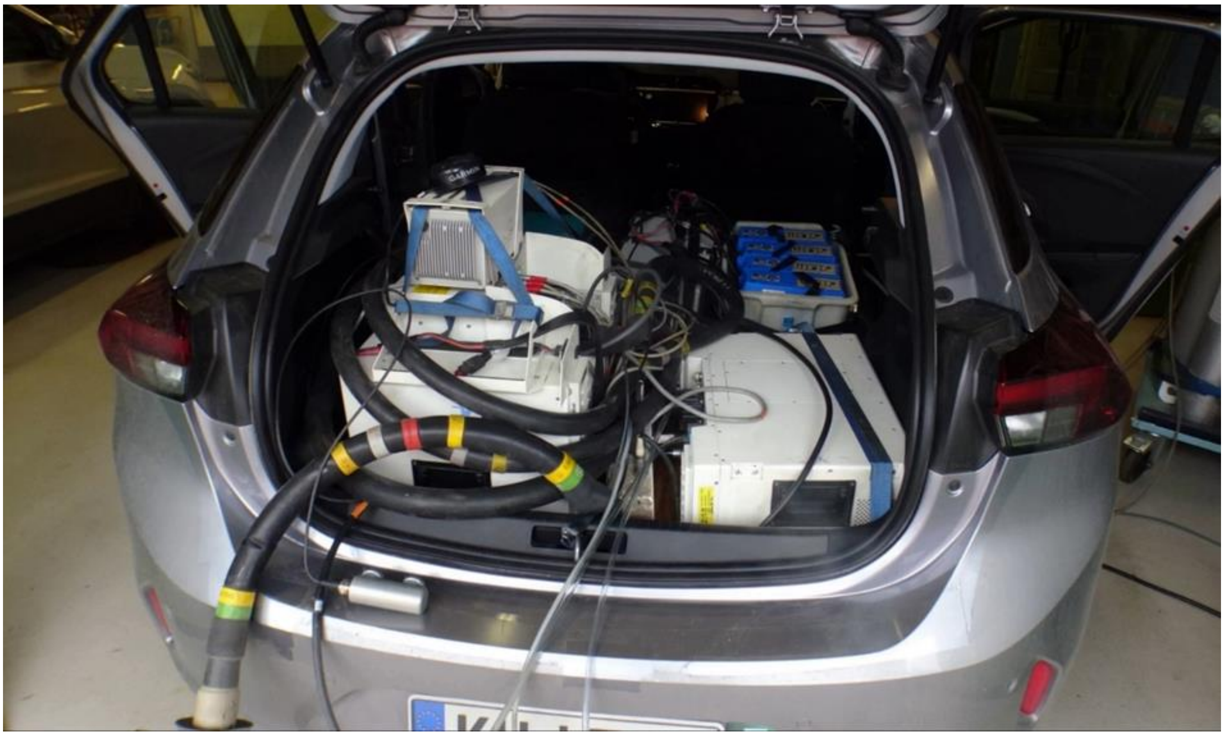


Figure 2-6: PEMS system installation in the boot of test car R5, Opel Corsa

Figure 2-7: Sampling probe and EFM installation (measures exhaust flow) at the back on test car R5, Opel Corsa

Note: in Figure 2-7 above the black and round GPS antenna pod is seen on the roof.

2.6 Execution of the tests

Each driver drove the route twice in succession during their allocated time. Between the two rides, a short 15 to 20 minutes pause was made for driver refreshment and data download. To avoid the busiest traffic times, timeslots were allocated in the morning hours (9:30 to 11:30) and in the afternoon (12:30 to 14:30), as the morning rush usually clears by 9 and does not start in the afternoon before 15. However, there were a few unfortunate occasions, when exceptionally heavy traffic was encountered, usually because of some incident or accident, rendering that ride unusable, at least for those parts of the route that were affected. A logbook was used to mark these drives that had exceptionally long driving time as “affected”. These runs were eventually disregarded in the analysis, as their presence could unduly skew the results.

The tests were run as six two-week campaigns, which allotted first two days for the installations and preparations of the measurement set-up, and then eight days for test rides, each allowing two drivers to drive twice. The first campaign was executed in March 2020, but then due to the outburst of the COVID-19 pandemic and the associated restraints, the work had to be halted for almost five months. However, as the pandemic situation was somewhat relieved in Finland during the summer months, work could be resumed with the exception that the driver was driving alone, whereas in the first campaign, there was a human co-pilot/instructor, who guided the driver where to drive. As it was no longer allowed for two people to stay in the car for such a long time, the co-driver was replaced with a regular GPS navigation aid device, and with a mobile phone connection allowing the driver and instructor to talk during the ride, if necessary.

The second campaign was run in August 2020, the third in late September/early October, and the fourth took place between mid to end of October. Then, due to the winter weather conditions affecting too much to the driving, the remaining two campaigns were postponed until next spring. Subsequently, the fifth campaign was executed from in May 2021, and the last remaining one in July 2021. Table 2.4 gives the exact dates of the campaigns, as well the ambient conditions (temperature, relative humidity) during the campaigns.

Table 2.4: Main characteristics PEMS test campaigns

#	Car	Start date	End date	Ambient temperature (°C)			Relative humidity (%)		
				Low	Average	High	Low	Average	High
1	R1	9.3.2020	20.3.2020	3.5	5.5	9.9	36.5	66.7	93.6
2	R2	17.8.2020	28.8.2020	13.5	20.2	25.5	41.4	56.1	88.0
3	R3	27.9.2020	9.10.2020	11.8	14.8	18.1	59.0	76.2	87.6
4	R4	14.10.2020	28.10.2020	2.4	8.9	12.8	53.1	78.3	94.9
5	R5	5.5.2021	21.5.2021	7.0	15.2	25.1	31.4	63.1	88.8
6	R6	7.6.2021	18.6.2021	19.0	24.0	29.5	24.8	38.7	61.9

As Table 2.4 shows, the overall ambient conditions did vary from day to day, and especially from one campaign to another. However, apart from some light rain or drizzle, all driving was conducted over normal street and road surface conditions. Furthermore, even if the ambient temperature varied between different campaigns, it was supposed not to have any major influence, as the car was always fully warmed-up before the test began. Also, ambient humidity is a parameter that may have some effect in emissions, NOx in particular, but this known effect was corrected in the post-processing of the data.

The general aim was that all the 15 drivers from the test pool would drive each of the six cars. However, difficulties in scheduling were encountered, and eventually, not every driver drove each of the cars. Table 2.5 gives the association of the drivers with the cars. Drivers from A to O are from the pool, but drivers P and Q were substitutes that were used in case no regular driver was able to drive on that occasion. These drivers were from the VTT's crew associated with these experiments and can be ranked as more professional test drivers rather than regular motorists.

Table 2.5 shows that of the pool of 15 drivers, eight managed to drive all six cars, five drove altogether five, and two drivers managed to drive only four cars. With the substitute drivers also counted in, one car was driven by 13 drivers, two cars by 14 different drivers, and three by 15 drivers in total. This gave a very broad spectrum of different driving styles, as the analysis will later reveal.

Table 2.5: Drivers' association with the test cars in PEMS tests

Car	Drivers																	
#	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	**Total**
R1	x	x	x		x	x	x	x		x	x	x	x	x	x		x	14
R2	x		x	x	x	x	x	x	x	x	x	x	x	x	x		x	15
R3	x	x	x	x	x	x		x	x	x	x	x	x	x	x		x	15
R4	x	x	x	x	x	x	x		x	x	x	x	x		x	x		14
R5	x		x	x		x	x	x	x	x	x	x	x	x	x	x		13
R6	x	x	x	x		x	x	x	x	x	x	x	x	x	x		x	15
Total	6	4	6	5	4	6	5	5	5	6	6	6	6	5	6	2	4	

2.7 Validation and quality assurance

The validity and quality of the test results were assured by the PEMS system internal validation scheme that oversaw the functions and performed several pre-run calibrations using standard gas mixtures with known concentrations, as well as post-checks, were drifts were measured. Subsequently, in the data post-processing, any drifts encountered were corrected. Also, ambient conditions were measured and recorded, and used to normalise the results.

Furthermore, the crew that were preparing the test car installations, managed and oversaw the test runs, as well as post-processed the collected data consisted of professionals, who have been successfully executing these kind of tests for several years and for tens of different cars.

2.8 Results on aggregated level

In this chapter a summary of the results in this experiment on an aggregate level is presented. The results are for the total trip, and presented for each car and each driver, as well as an average for all the drivers for each car, and an average for all tested cars. In Chapter 2.9, results are addressed on a second-by-second level.

Table 2.6 collects the main descriptive parameters of the test runs. It presents the results as an average of the two subsequent runs for each driver, as well as an average for the given car. Although as Table 2.4 shows, ambient conditions did differ between drivers and campaigns, those were considered as random parameters like the traffic situation, and subsequently were not included in this high-level analysis, mainly due to the corrections made in the post-processing that were supposed to eliminate their effects. However, due to the active regeneration occurring in some test runs, those cases were not included in the analysis, and only the other run was reported.

Furthermore, in some very few cases due to problems with the instruments, some parameters could not be collected, mainly engine speed and power & work, as the OBD connection did not always function as intended. Those are marked in the table with “n/a”.

Table 2.6: Main descriptive parameters of the tests for all cars and drivers

	DRIVER POOL															SUBSTITUTES			AVG	
Trip Duration	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	2918	s
Car R1	2824	3157	3010	o	2981	2772	2646	2848	o	2788	2748	2882	2897	3039	2771	o	2793	o	2868	-2 %
Car R2	2816	o	3135	2835	2851	3032	2907	2804	2804	2741	2825	3319	3087	3277	2808	o	3094	2899	2952	1 %
Car R3	2875	2955	3024	2868	2791	2968	o	2862	2707	2676	2713	3148	2901	2898	2734	o	2864	o	2865	-2 %
Car R4	2879	3081	3076	2786	2913	2918	2747	o	2872	2667	2879	3132	2985	o	2902	3062	o	o	2921	0 %
Car R5	2819	o	3007	2912	o	2935	2783	2946	2905	2872	3029	3452	2999	3028	2899	o	o	o	2977	2 %
Car R6	2847	3013	3001	2745	o	2899	2739	2944	2881	2609	2898	3165	3175	3048	2788	o	3135	o	2926	0 %
Trip Distance	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	30.841	km
Car R1	30.030	29.980	30.010	o	30.010	30.020	30.010	30.020	o	30.260	30.050	30.005	30.010	29.990	29.995	o	29.990	o	30.027	-3 %
Car R2	31.120	o	31.115	31.135	31.160	31.110	31.125	31.125	31.155	31.095	31.160	31.415	31.140	32.545	31.130	o	31.075	31.120	31.233	1 %
Car R3	30.890	31.430	30.880	30.915	30.925	30.875	o	30.875	30.920	30.890	31.060	30.880	30.910	30.900	30.915	o	30.875	o	30.943	0 %
Car R4	31.070	31.160	31.280	31.165	31.185	31.180	31.160	o	31.140	31.150	31.305	31.165	31.155	o	31.180	31.190	o	o	31.178	1 %
Car R5	31.260	o	31.000	31.245	o	31.125	31.315	31.690	31.075	31.215	31.490	31.040	31.215	31.325	31.090	o	o	o	31.238	1 %
Car R6	30.775	30.320	30.350	30.360	o	30.360	30.180	30.345	30.315	30.325	30.380	30.345	31.015	30.690	30.340	o	30.325	o	30.428	-1 %
Trip Av.speed	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	38.2	km/h
Car R1	38.3	34.3	35.9	o	36.3	39.0	40.9	38.0	o	39.1	39.4	37.5	37.3	35.5	39.0	o	38.8	o	37.8	-1 %
Car R2	39.8	o	35.8	39.5	39.4	37.0	38.6	40.0	40.0	40.8	39.7	34.1	36.3	35.8	39.9	o	36.2	38.8	38.2	0 %
Car R3	38.7	38.3	36.8	38.8	39.9	37.5	o	38.8	41.2	41.6	41.2	35.3	38.4	38.4	40.7	o	38.8	o	39.0	2 %
Car R4	39.0	36.4	36.6	40.3	38.5	38.5	40.8	o	39.0	42.1	39.2	35.8	38.7	o	38.7	36.7	o	o	38.6	1 %
Car R5	40.0	o	37.1	38.6	o	38.2	40.5	38.8	38.5	39.1	37.4	33.4	37.5	37.2	38.6	o	o	o	38.0	-1 %
Car R6	38.9	36.3	36.4	39.8	o	37.8	39.7	37.1	37.9	41.8	37.8	34.6	35.2	36.3	39.2	o	34.9	o	37.6	-2 %
Trip Fuel Econ.	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	5.44	L/100 km
Car R1 (P)	4.91	4.59	4.72	o	5.58	5.03	5.88	5.77	o	6.49	5.41	5.13	5.20	5.32	5.59	o	4.60	o	5.30	-3 %
Car R2 (D)	4.35	o	4.22	4.66	4.48	4.29	4.73	4.38	4.77	5.11	4.52	4.59	4.44	4.46	4.59	o	4.35	4.44	4.52	-17 %
Car R3 (P)	5.02	4.92	5.20	5.42	5.30	4.99	o	5.67	5.91	5.51	5.48	5.29	4.67	4.67	5.61	o	4.65	o	5.22	-4 %
Car R4 (P)	6.92	6.83	6.95	7.03	6.80	7.00	7.26	o	8.25	7.09	6.97	7.69	6.89		6.97	6.43	o	o	7.07	30 %
Car R5 (P)	5.68	o	5.47	5.85	o	5.89	6.41	6.57	7.09	6.35	6.04	7.03	5.72	6.00	6.45	o	o	o	6.15	13 %
Car R6 (D)	4.16	3.90	4.08	4.18	o	4.04	4.79	4.81	5.18	4.82	3.84	4.25	3.93	4.12	4.79	o	4.56	o	4.36	-20 %
Avg Eng. Speed	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	1588	rpm
Car R1	1455	1548	1525	o	1799	1771	1848	2003	o	1954	1761	1555	1775	1648	1829	o	1464	o	1710	8 %
Car R2	1383	o	1353	1382	1378	1349	1369	1389	1383	1385	1378	1331	1335	1357	1369	o	1361	1458	1372	-14 %
Car R3	1407	1428	1563	1735	1645	1664	o	1691	1634	1767	1573	1495	1499	1525	1825	o	1389	o	1589	0 %
Car R4	n/a	n/a	n/a	1757	1728	1765	1790	o	1751	1788	1745	1695	1760	o	1722	1696	o	o	1745	10 %
Car R5	1674	o	1507	1643	o	1385	1705	1876	1857	1705	1906	1613	1680	1538	1460	o	o	o	1644	4 %
Car R6	1299	1296	1454	1698	o	1459	1522	1591	1571	1635	1337	1367	n/a	1443	1534	o	1311	o	1465	-8 %
Avg Trip Power	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	11.4	kW
Car R1	7.0	6.0	6.2	o	6.9	6.8	8.1	7.7	o	8.3	7.3	6.6	6.9	6.6	7.3	o	6.4	o	7.0	-38 %
Car R2	17.6	o	16.4	15.9	17.5	16.5	16.7	16.2	16.6	17.4	17.7	16.8	16.5	16.9	16.6	o	16.6	17.3	16.8	48 %
Car R3	9.7	9.8	9.9	11.6	11.5	10.7	o	11.2	11.8	12.3	11.2	9.9	10.0	10.1	12.4	o	9.4	o	10.8	-5 %
Car R4	n/a	n/a	n/a	13.8	13.1	13.7	13.7	o	13.4	13.3	13.3	13.4	12.6		12.9	12.2	o	o	13.2	16 %
Car R5	11.2	o	10.8	11.6	o	10.3	11.7	11.4	11.9	11.7	12.5	11.6	11.2	10.9	10.9	o	o	o	11.3	0 %
Car R6	9.7	8.6	8.4	8.2	o	8.3	9.5	9.2	9.9	10.0	8.7	8.5	n/a	8.3	9.7	o	9.3	o	9.0	-21 %
Trip Work																			9.20	kWh
Car R1	5.48	5.27	5.17	o	5.74	5.26	5.93	6.05	o	6.46	5.58	5.31	5.53	5.56	5.64	o	4.99	o	5.57	-39 %
Car R2	13.8	o	14.3	12.5	13.8	13.9	13.4	12.6	12.9	13.3	13.9	15.5	14.2	15.3	13.0	o	14.3	13.9	13.8	50 %
Car R3	7.77	8.06	8.36	9.21	8.91	8.80	o	8.90	8.88	9.14	8.30	8.66	8.09	8.13	9.38	o	7.50	o	8.54	-7 %
Car R4	n/a	n/a	n/a	10.7	10.6	11.1	10.5	o	10.7	9.9	10.7	11.7	10.4	o	10.4	10.7	o	o	10.7	16 %
Car R5	9.10	o	9.26	9.33	o	9.84	9.02	9.18	9.73	9.02	9.88	9.26	9.36	9.46	9.33	o	o	o	9.36	2 %
Car R6	7.72	7.21	6.98	6.26	o	6.70	7.24	7.53	7.89	7.28	6.99	7.48	n/a	7.00	7.55	o	8.11	o	7.28	-21 %

5.5 Average result for the driver | o The driver did not drive this car | n/a Result is missing due to malfunctios

4.38 Only one trip, due to the active regeneration event on the other trip

At first these parameters were used to assess the spread of different driving styles found amongst the drivers. This included calculating an average for all the results for that given parameter per each car, and then observing the spread of the driver-specific results around that average. This assessment led to Table 2.7 that presents these driver-to-average deviations for each driver. The colour-coding is supposed to help to see the scores as the more green the cell colour is, the more the result is below average (denotes “good” driving style) or the more red the cell colour is, the more the result is above average (denotes “bad” driving style).

Table 2.7: Driver-to-average spread for each driver and car

	DRIVER POOL															AVG	MIN	MAX	TOTAL
Trip Av.speed	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	km/h	-9 %	9 %	18 %
Car R1	1.3 %	-9.3 %	-5.0 %	o	-4.1 %	3.2 %	8.1 %	0.4 %	o	3.4 %	4.2 %	-0.8 %	-1.3 %	-6.0 %	3.2 %	37.8	-9 %	8 %	17 %
Car R2	4.2 %	o	-1.5 %	8.9 %	8.3 %	1.8 %	6.4 %	10.0 %	10.2 %	12.4 %	9.3 %	-6.1 %	0.0 %	-1.6 %	9.9 %	38.2	-6 %	12 %	19 %
Car R3	-0.7 %	-1.6 %	-5.7 %	-0.4 %	2.4 %	-3.8 %	o	-0.3 %	5.7 %	6.6 %	5.8 %	-9.3 %	-1.5 %	-1.4 %	4.5 %	39.0	-9 %	7 %	16 %
Car R4	1.1 %	-5.6 %	-5.1 %	4.4 %	0.0 %	-0.1 %	5.9 %	o	1.2 %	9.1 %	1.5 %	-7.1 %	0.3 %	o	0.3 %	38.6	-7 %	9 %	16 %
Car R5	5.3 %	o	-2.2 %	1.8 %	o	0.7 %	6.7 %	2.3 %	1.5 %	3.1 %	-1.4 %	-12.1 %	-1.1 %	-1.9 %	1.7 %	38.0	-12 %	7 %	19 %
Car R6	3.6 %	-3.5 %	-3.1 %	6.0 %	o	0.5 %	5.6 %	-1.2 %	0.9 %	11.4 %	0.6 %	-8.0 %	-6.4 %	-3.5 %	4.3 %	37.6	-8 %	11 %	19 %
Trip Av. Eng. Speed	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	rpm	-10 %	12 %	22 %
Car R1	-14.9 %	-9.4 %	-10.8 %	o	5.2 %	3.6 %	8.1 %	17.1 %	o	14.3 %	3.0 %	-9.0 %	3.8 %	-3.6 %	7.0 %	1710	-15 %	17 %	32 %
Car R2 (A)	0.8 %	o	-1.4 %	0.7 %	0.4 %	-1.7 %	-0.2 %	1.2 %	0.8 %	0.9 %	0.4 %	-3.0 %	-2.7 %	-1.1 %	-0.3 %	1372	-3 %	6 %	9 %
Car R3	-11.4 %	-10.1 %	-1.7 %	9.2 %	3.5 %	4.7 %	o	6.4 %	2.8 %	11.2 %	-1.0 %	-6.0 %	-5.7 %	-4.1 %	14.8 %	1589	-13 %	15 %	27 %
Car R4 (A)	n/a	n/a	n/a	0.7 %	-1.0 %	1.2 %	2.6 %	o	0.3 %	2.4 %	0.0 %	-2.9 %	0.8 %	o	-1.3 %	1745	-3 %	3 %	5 %
Car R5	1.8 %	o	-8.3 %	-0.1 %	o	-15.7 %	3.8 %	14.2 %	13.0 %	3.8 %	16.0 %	-1.9 %	2.2 %	-6.4 %	-11.2 %	1644	-16 %	16 %	32 %
Car R6	-11.4 %	-11.5 %	-0.8 %	15.9 %	o	-0.5 %	3.8 %	8.6 %	7.2 %	11.6 %	-8.8 %	-6.7 %	n/a	-1.5 %	4.7 %	1465	-12 %	16 %	27 %
Trip Avg Power	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	kW	-10 %	11 %	20 %
Car R1	-0.4 %	-14.2 %	-11.8 %	o	-1.2 %	-2.6 %	15.0 %	9.1 %	o	18.9 %	4.3 %	-5.5 %	-2.0 %	-6.1 %	4.5 %	7.0	-14 %	19 %	33 %
Car R2	4.8 %	o	-2.4 %	-5.4 %	3.7 %	-2.0 %	-1.1 %	-4.0 %	-1.3 %	3.5 %	5.4 %	-0.1 %	-1.8 %	0.1 %	-1.1 %	16.8	-5 %	5 %	11 %
Car R3	-9.7 %	-8.8 %	-7.7 %	7.4 %	6.6 %	-0.9 %	o	4.0 %	9.7 %	14.1 %	3.9 %	-8.1 %	-6.8 %	-6.2 %	14.7 %	10.8	-12 %	15 %	27 %
Car R4	n/a	n/a	n/a	4.4 %	-1.2 %	3.3 %	3.9 %	o	1.7 %	0.8 %	0.6 %	1.3 %	-5.0 %	o	-2.2 %	13.2	-8 %	4 %	12 %
Car R5	-1.2 %	o	-4.7 %	2.4 %	o	-9.3 %	3.2 %	0.7 %	5.2 %	3.2 %	10.3 %	2.4 %	-0.9 %	-3.3 %	-3.9 %	11.3	-9 %	10 %	20 %
Car R6	7.6 %	-4.5 %	-7.4 %	-9.0 %	o	-7.8 %	5.5 %	2.2 %	9.1 %	11.2 %	-3.7 %	-5.7 %	n/a	-8.6 %	7.9 %	9.03	-9 %	11 %	20 %
Trip Work	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	kWh	-9 %	11 %	20 %
Car R1	-1.6 %	-5.3 %	-7.1 %	o	3.0 %	-5.6 %	6.4 %	8.6 %	o	16.0 %	0.2 %	-4.7 %	-0.7 %	-0.2 %	1.2 %	5.57	-10 %	16 %	26 %
Car R2	-0.1 %	o	3.7 %	-9.1 %	0.2 %	0.7 %	-2.7 %	-8.7 %	-6.2 %	-3.9 %	0.9 %	12.4 %	2.7 %	11.2 %	-6.0 %	13.8	-9 %	12 %	21 %
Car R3	-9.0 %	-5.6 %	-2.1 %	7.9 %	4.3 %	3.0 %	o	4.2 %	4.0 %	7.0 %	-2.8 %	1.4 %	-5.3 %	-4.8 %	9.9 %	8.54	-12 %	10 %	22 %
Car R4	n/a	n/a	n/a	0.3 %	-0.9 %	3.7 %	-1.6 %	0.0 %	0.6 %	-7.4 %	0.3 %	9.4 %	-2.3 %	o	-2.1 %	10.7	-7 %	9 %	17 %
Car R5	-2.9 %	o	-1.1 %	-0.4 %	o	5.1 %	-3.7 %	-2.0 %	3.9 %	-3.7 %	5.5 %	-1.1 %	-0.1 %	1.0 %	-0.4 %	9.36	-4 %	6 %	9 %
Car R6	6.0 %	-1.0 %	-4.2 %	-14.0 %	o	-8.0 %	-0.6 %	3.4 %	8.4 %	0.0 %	-4.0 %	2.7 %	n/a	-3.9 %	3.6 %	7.28	-14 %	11 %	25 %
Fuel Economy	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	L/100 km	-11 %	16 %	27 %
Car R1 (P)	-7.4 %	-13.5 %	-10.9 %	o	5.3 %	-5.1 %	10.9 %	8.8 %	o	22.4 %	2.0 %	-3.2 %	-1.9 %	0.4 %	5.4 %	5.30	-13 %	22 %	36 %
Car R2 (D)	-3.8 %	o	-6.7 %	3.0 %	-1.0 %	-5.1 %	4.6 %	-3.1 %	5.4 %	12.9 %	0.0 %	1.5 %	-1.8 %	-1.4 %	1.5 %	4.52	-7 %	13 %	20 %
Car R3 (P)	-3.9 %	-5.7 %	-0.3 %	3.8 %	1.6 %	-4.5 %	o	8.7 %	13.2 %	5.5 %	4.9 %	1.3 %	-10.5 %	-10.6 %	7.4 %	5.22	-11 %	13 %	24 %
Car R4 (P)	-2.2 %	-3.5 %	-1.8 %	-0.6 %	-3.9 %	-1.1 %	2.6 %	o	16.6 %	0.2 %	-1.5 %	8.6 %	-2.7 %	o	-1.5 %	7.07	-9 %	17 %	26 %
Car R5 (P)	-7.8 %	o	-11.2 %	-5.0 %	o	-4.4 %	4.1 %	6.7 %	15.1 %	3.2 %	-1.9 %	14.1 %	-7.1 %	-2.6 %	4.7 %	6.15	-11 %	15 %	26 %
Car R6 (D)	-4.6 %	-10.7 %	-6.4 %	-4.3 %	o	-7.4 %	9.7 %	10.2 %	18.7 %	10.5 %	-11.9 %	-2.7 %	-9.9 %	-5.6 %	9.8 %	4.36	-12 %	19 %	31 %

-9.0 %	Drivers average result is below average for this car	o	Driver did not drvie this car
6.0 %	Drivers average result is above average for this car	n/a	Result not available due to malfunctions

According to Table 2.7, the total score for trip parameters shows that the deviations of the scored parameters typically yield to ± 10 % span, but fuel consumption spreads more, having on average almost a 30 % span between the lowest and highest result, with one car up to 36 %. As this was the first car, it is also possible, that some of that spread was due to the novelty of the test set-up. It was also worth noting that average engine speed varied much less (5% and 7%) with the two cars having automated gearbox, marked with (A), compared to those with manual gear selection, where the deviations were around 30 % between drivers.

Finally, the scoring was combined, counting an average for each driver of the car-specific scores. In this total score, the trip time and distance were excluded, as those were combined in average speed. Table 2.8 shows this combined scoring for each driver.

As Table 2.8 shows, the driving styles of the drivers did differ from each other, and with a quite large margin. The “best” driver (B) had a score -7.1 %, whereas the “worst” driver (J) had a score +6.3 %, so the span is over 13 %.

It is also worth noting that the Total Trip Score in Table 2.8, which is an average of the four trip-related main parameters, also correlates quite well with the Fuel Economy Score, as we see usually green or red colour in both Total Trip and Fuel Economy Scores for individual drivers.

Table 2.8: Total Trip and Fuel Economy Scores each driver

	DRIVER POOL														
Driver #	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Car count	6	4	6	5	4	6	5	5	5	6	6	6	6	5	6
Trip Av.speed	2.5 %	-5.0 %	-3.8 %	4.1 %	1.7 %	0.4 %	6.5 %	2.3 %	3.9 %	7.7 %	3.3 %	-7.2 %	-1.7 %	-2.9 %	4.0 %
Trip Av. Eng. Speed	-7.0 %	-10.4 %	-4.6 %	5.3 %	2.0 %	-1.4 %	3.6 %	9.5 %	4.8 %	7.4 %	1.6 %	-4.9 %	-0.3 %	-3.3 %	2.3 %
Trip Avg Power	0.2 %	-9.2 %	-6.8 %	0.0 %	2.0 %	-3.2 %	5.3 %	2.4 %	4.9 %	8.6 %	3.5 %	-2.6 %	-3.3 %	-4.8 %	3.3 %
Trip Work	-1.5 %	-4.0 %	-2.2 %	-3.1 %	1.7 %	-0.2 %	-0.4 %	0.9 %	2.1 %	1.4 %	0.0 %	3.4 %	-1.1 %	0.7 %	1.0 %
Total Trip Score	-1.5 %	-7.1 %	-4.3 %	1.6 %	1.8 %	-1.1 %	3.8 %	3.8 %	3.9 %	6.2 %	2.1 %	-2.8 %	-1.6 %	-2.6 %	2.7 %
Fuel Economy Score	-4.9 %	-8.3 %	-6.2 %	-0.6 %	0.5 %	-4.6 %	6.4 %	6.2 %	13.8 %	9.1 %	-1.4 %	3.3 %	-5.6 %	-4.0 %	4.6 %
Combined Score	-3.2 %	-7.7 %	-5.3 %	0.5 %	1.1 %	-2.8 %	5.1 %	5.0 %	8.9 %	7.7 %	0.3 %	0.2 %	-3.6 %	-3.3 %	3.6 %
Ranking	5	1	2	9	10	6	13	12	15	14	8	7	3	4	11

We then analysed the consistency of the drivers’ driving by comparing the results of the two successive rides they each rode. Less deviation between the results can be seen as, a) consistent driving abilities, but also, b) the surrounding traffic influence was not too high. Table 2.9 presents the results of this scoring.

Regarding the two diesel cars, there were some runs that induced an active regeneration event with both cars. That had implications for the fuel economy, and subsequently also to emissions. For car R2, those three incidents that include an active regeneration event are marked with a frame (drivers D, H and O), and for that reason, we have not presented any consistency score. For Car R6, for similar reason results are missing for drivers K and O. However, we feel that these events did not affect the other driving parameters like average speed, engine speed, power or work. Thus, consistency was assessed on those parameters even with these affected cases.

According to the results, the most consistent drivers were able to replicate their two successive runs by a quite high degree. In summary, the average consistency was about 1.7 % overall, but the driver with the high consistency (E) could yield to a figure less than 1 %, whereas the least consistent one (H) had a score of 2.5 %. Even then we can say that the different driving style profiles presented by this pool of drivers were quite solid, and gave a good basis for applying correlation between driving style and exhaust emissions in Task 3.5.

Table 2.9: Driver consistency for each driver and car

Trip Av.speed	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	AVG	MIN	MAX
	DRIVER POOL															AVG	MIN	MAX
Car R1	1.4 %	5.2 %	1.2 %	o	1.5 %	1.1 %	1.8 %	1.4 %	o	0.7 %	0.1 %	0.0 %	0.1 %	0.6 %	1.7 %	1.3 %	0.0 %	5.2 %
Car R2	3.7 %	o	3.8 %	1.0 %	1.0 %	3.5 %	5.0 %	1.3 %	2.2 %	0.6 %	0.2 %	1.5 %	1.2 %	0.4 %	1.9 %	2.0 %	0.2 %	5.0 %
Car R3	0.4 %	2.4 %	0.0 %	2.0 %	0.5 %	2.1 %	o	0.3 %	4.0 %	0.1 %	1.1 %	1.9 %	1.6 %	2.7 %	1.6 %	1.5 %	0.0 %	4.0 %
Car R4	6.2 %	0.5 %	0.4 %	1.0 %	0.8 %	3.4 %	1.6 %	o	0.4 %	1.3 %	0.9 %	1.2 %	2.5 %	o	1.8 %	1.7 %	0.4 %	6.2 %
Car R5	3.9 %	0.0 %	1.0 %	0.7 %	o	3.1 %	1.4 %	4.6 %	3.1 %	1.1 %	0.6 %	3.0 %	4.7 %	0.6 %	0.5 %	2.0 %	0.0 %	4.7 %
Car R6	1.8 %	2.7 %	0.9 %	1.0 %	o	4.3 %	1.1 %	2.5 %	1.9 %	0.1 %	3.6 %	4.2 %	0.9 %	1.3 %	2.0 %	2.0 %	0.1 %	4.3 %
Average	2.9 %	2.2 %	1.2 %	1.1 %	0.9 %	2.9 %	2.2 %	2.0 %	2.4 %	0.6 %	1.1 %	2.0 %	1.8 %	1.1 %	1.6 %	1.7 %	0.1 %	4.9 %

Trip Fuel Economy	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	AVG	MIN	MAX
Car R1 (P)	0.4 %	0.8 %	1.5 %	o	2.5 %	2.0 %	3.1 %	0.3 %	o	0.4 %	4.7 %	2.3 %	2.7 %	2.4 %	2.8 %	2.0 %	0.3 %	4.7 %
Car R2 (D)	2.1 %	o	1.9 %	n/a	0.6 %	1.2 %	0.6 %	n/a	0.7 %	2.1 %	0.4 %	0.7 %	0.5 %	0.2 %	n/a	1.0 %	0.2 %	2.1 %
Car R3 (P)	2.5 %	2.4 %	1.2 %	1.2 %	0.2 %	3.1 %	o	0.2 %	2.5 %	1.7 %	1.0 %	3.9 %	1.5 %	4.0 %	3.5 %	2.1 %	0.2 %	4.0 %
Car R4 (P)	2.3 %	1.7 %	0.4 %	0.4 %	1.4 %	0.1 %	2.7 %	o	0.1 %	2.8 %	0.2 %	0.8 %	3.3 %	o	0.2 %	1.3 %	0.1 %	3.3 %
Car R5 (P)	3.1 %	o	1.7 %	2.8 %	o	2.1 %	3.8 %	2.4 %	2.0 %	2.5 %	1.2 %	2.8 %	2.7 %	0.1 %	1.5 %	2.2 %	0.1 %	3.8 %
Car R6 (D)	1.9 %	4.5 %	2.2 %	1.3 %	0.0 %	3.0 %	3.0 %	3.4 %	1.8 %	1.0 %	n/a	2.9 %	0.8 %	1.8 %	n/a	2.1 %	0.0 %	4.5 %
Average	2.0 %	2.3 %	1.5 %	1.4 %	0.9 %	1.9 %	2.6 %	1.6 %	1.4 %	1.8 %	1.5 %	2.2 %	1.9 %	1.7 %	2.0 %	1.8 %	0.1 %	3.7 %

Trip Av. Eng. Speed	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	AVG	MIN	MAX
Car R1	1.2 %	1.8 %	1.0 %	o	3.0 %	0.1 %	0.8 %	0.0 %	o	2.7 %	0.1 %	1.2 %	0.7 %	1.9 %	4.2 %	1.4 %	0.0 %	4.2 %
Car R2 (A)	1.7 %	o	1.4 %	0.9 %	0.4 %	1.3 %	1.7 %	0.9 %	0.6 %	0.5 %	0.1 %	0.6 %	0.3 %	0.7 %	0.2 %	0.8 %	0.1 %	1.7 %
Car R3	1.5 %	0.2 %	0.5 %	1.1 %	1.6 %	1.1 %	o	5.6 %	2.7 %	1.2 %	n/a	1.9 %	1.7 %	0.0 %	2.5 %	1.7 %	0.0 %	5.6 %
Car R4 (A)	n/a	n/a	n/a	0.4 %	0.1 %	2.6 %	0.4 %	o	0.1 %	0.8 %	n/a	0.2 %	0.9 %	o	0.5 %	0.7 %	0.1 %	2.6 %
Car R5	n/a	o	n/a	2.7 %	o	2.0 %	1.4 %	2.0 %	4.0 %	n/a	n/a	n/a	n/a	1.3 %	0.3 %	2.0 %	0.3 %	4.0 %
Car R6	n/a	3.5 %	1.1 %	1.5 %	0.0 %	1.9 %	n/a	0.5 %	0.2 %	0.4 %	2.0 %	0.8 %	n/a	n/a	1.0 %	1.2 %	0.0 %	3.5 %
Average	1.5 %	1.8 %	1.0 %	1.3 %	1.0 %	1.5 %	1.1 %	1.8 %	1.5 %	1.1 %	0.7 %	0.9 %	0.9 %	1.0 %	1.4 %	1.3 %	0.1 %	3.6 %

Trip Power	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	AVG	MIN	MAX
Car R1	1.1 %	2.9 %	1.1 %	o	0.4 %	0.7 %	0.8 %	0.7 %	o	1.1 %	3.8 %	2.8 %	2.3 %	2.4 %	2.7 %	1.7 %	0.4 %	3.8 %
Car R2	3.5 %	o	1.6 %	7.9 %	0.9 %	0.8 %	4.9 %	5.5 %	0.6 %	0.9 %	0.4 %	0.1 %	0.1 %	0.8 %	6.6 %	2.5 %	0.1 %	7.9 %
Car R3	1.4 %	0.4 %	0.4 %	1.1 %	2.9 %	0.1 %	o	4.3 %	0.9 %	1.1 %	n/a	0.7 %	2.2 %	0.3 %	3.9 %	1.5 %	0.1 %	4.3 %
Car R4	n/a	n/a	n/a	0.5 %	0.1 %	3.4 %	0.6 %	o	4.4 %	1.8 %	n/a	0.4 %	0.4 %	o	0.1 %	1.3 %	0.1 %	4.4 %
Car R5	n/a	o	n/a		o	2.0 %	1.2 %	1.1 %	3.2 %	n/a	n/a	n/a	n/a	0.1 %	0.5 %	1.3 %	0.1 %	3.2 %
Car R6	n/a	2.6 %	2.3 %	1.2 %	0.0 %	0.3 %	n/a	5.4 %	0.1 %	0.8 %	2.6 %	1.9 %	n/a	n/a	0.2 %	1.6 %	0.0 %	5.4 %
Average	2.0 %	2.0 %	1.3 %	2.7 %	0.8 %	1.2 %	1.9 %	3.4 %	1.8 %	1.1 %	2.2 %	1.2 %	1.2 %	0.9 %	2.3 %	1.7 %	0.1 %	4.8 %

Trip Work	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	AVG	MIN	MAX
Car R1	0.4 %	2.3 %	2.3 %	o	1.8 %	1.8 %	2.6 %	0.7 %	o	0.5 %	3.9 %	2.7 %	2.4 %	1.7 %	1.2 %	1.9 %	0.4 %	3.9 %
Car R2	0.2 %	o	2.2 %	8.9 %	0.1 %	2.7 %	0.0 %	6.7 %	1.6 %	1.4 %	0.6 %	2.4 %	1.3 %	4.8 %	4.7 %	2.7 %	0.0 %	8.9 %
Car R3	0.8 %	4.5 %	0.3 %	1.0 %	2.4 %	2.1 %	o	4.0 %	3.0 %	0.9 %	n/a	2.5 %	0.6 %	2.5 %	2.2 %	2.1 %	0.3 %	4.5 %
Car R4	n/a	n/a	n/a	0.5 %	0.7 %	0.0 %	2.1 %	o	3.9 %	0.6 %	n/a	0.7 %	2.2 %	o	1.8 %	1.4 %	0.0 %	3.9 %
Car R5	n/a	o	n/a		o	1.4 %	0.1 %	4.7 %	0.2 %	n/a	n/a	n/a	n/a	0.8 %	0.6 %	1.3 %	0.1 %	4.7 %
Car R6	n/a	0.1 %	3.2 %	0.2 %	0.0 %	4.6 %	n/a	2.9 %	1.9 %	0.8 %	1.0 %	2.4 %	n/a	n/a	2.2 %	1.8 %	0.0 %	4.6 %
Average	0.5 %	2.3 %	2.0 %	2.6 %	1.0 %	2.1 %	1.2 %	3.8 %	2.1 %	0.9 %	1.9 %	2.2 %	1.6 %	2.4 %	2.1 %			

0.5 %	Difference of driver's two runs, smaller than average	n/a	Result not available due to malfunctions
4.8 %	Difference of driver's two runs, larger than average	n/a	Result not available, as the other run included a DPF regeneration
o	Driver did not drive this car		

Driver #	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	AVG	MIN	MAX
Average Consistency	1.8 %	2.1 %	1.4 %	1.8 %	0.9 %	1.9 %	1.8 %	2.5 %	1.9 %	1.1 %	1.5 %	1.7 %	1.5 %	1.4 %	1.9 %	1.7 %	0.9 %	2.5 %
Ranking	8	14	3	11	1	13	9	15	10	2	5	7	6	4	12			

Regarding the most important results, the actual tailpipe emissions, Table 2.10 summarises driver-specific results for each car. For each car, an average (AVG) is calculated from all driver's results, and the type approval (TA) value for the given car is also presented. Type approval values are sourced from the official registration data of the cars.

As already mentioned, there were active regeneration events that took place when testing the diesel cars (R2 and R6). The results from these "affected" tests are marked with a frame also in this table. For those runs the result is from the clean run only, and the "affected" results are not accounted for, because those would skew the analysis too much. Furthermore, with car R2 there were also some instrument faults that left some test runs without a PN result. Thus, those drivers' results are from only one trip, and subsequently also marked with a frame.

![modales logo]

Table 2.10: Exhaust emissions for each driver and car

		TEST DRIVER POOL															SUBSTITUTES			AVG	TA
CO_2	Fuel	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	mg/km	mg/km
Car R1	P	112	104	107	o	127	114	133	131	o	147	122	117	118	121	127	o	105	o	120	99
Car R2	D	114	o	111	*122*	117	113	125	*115*	125	134	119	121	116	117	*120*	o	114	116	119	141
Car R3	P	113	111	117	122	120	112	o	128	133	124	124	119	106	105	127	o	105	o	118	115
Car R4	P	157	155	158	159	154	158	164	o	186	161	157	174	155	o	157	145	o	o	160	153
Car R5	P	128	o	123	132	o	133	145	148	159	143	136	158	129	135	145	o	o	o	139	117
Car R6	D	109	102	107	110	o	106	126	127	136	127	*110*	112	103	108	*135*	o	*126*	o	116	140
CO	Fuel	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	mg/km	mg/km
Car R1	P	193	127	128	o	152	170	302	194	o	252	275	124	145	195	142	o	180	o	184.2	355.8
Car R2	D	due to analyser malfunction, data is missing																			
Car R3	P	11.5	2.6	1.9	2.1	3.4	12.1		6.7	5.4	3.9	5.2	0.8	0.4	0.9	1.7	o	1.0	o	4.0	221
Car R4	P	223	153	184	197	204	191	305		397	304	220	230	181		199	412	o	o	242.8	531.7
Car R5	P	239	o	189	274	o	286	500	393	635	336	315	302	228	276	369	o	o	o	321.9	508.7
Car R6	D	1.0	5.4	0.7	7.7	o	5.4	31.0	24.8	8.5	34.7	*0.8*	7.9	23.4	8.7	*7.9*	o	*2.5*	o	11.4	56.2
NOx	Fuel	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	mg/km	mg/km
Car R1	P	320.0	109.0	106.6	o	72.8	87.9	200.1	88.3	o	88.6	137.1	140.3	119.2	135.8	65.0	o	265.5	o	138.3	41.2
Car R2	D	18.2	o	17.0	*19.4*	9.3	25.2	29.9	*21.9*	43.3	48.9	14.4	21.7	14.3	23.0	*18.1*	o	22.5	31.3	23.7	29.2
Car R3	P	9.3	6.2	8.6	11.7	10.7	14.4		11.7	9.9	8.7	10.8	8.9	9.4	12.9	7.4	o	14.5	o	10.3	34.1
Car R4	P	7.6	9.2	3.7	10.2	5.7	7.8	10.8	0.0	11.8	10.8	10.0	9.5	13.1	0.0	12.8	6.4	o	o	9.2	17.5
Car R5	P	22.0	o	25.7	17.0	o	11.0	13.2	9.8	16.8	11.7	27.7	31.9	13.5	16.3	20.2	o	o	o	17.7	14.2
Car R6	D	43.0	56.0	30.1	38.9	o	43.4	45.4	60.1	42.8	43.9	61.1	44.8	34.1	30.1	51.8	o	48.1	o	44.9	34.9
PN	Fuel	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	$\#10^{11}$/km	$\#10^{11}$/km
Car R1	P	12.0	9.0	6.6	o	8.8	8.2	11.5	11.5	o	11.5	10.0	7.9	9.9	11.5	9.6	o	8.7	o	9.75	18.40
Car R2	D	0.047	o	n/a	*0.011*	0.010	0.008	n/a	*0.008*	0.011	0.010	0.008	n/a	n/a	0.010	*0.011*	o	0.008	0.008	0.01	0.02
Car R3	P	0.39	0.29	0.31	0.38	0.39	0.36		0.33	0.48	0.59	0.31	0.23	0.18	0.25	0.20	o	0.18	o	0.32	1.08
Car R4	P	0.27	0.32	0.08	0.51	0.34	0.61	0.79	0.00	1.15	0.82	0.25	0.39	0.59	0.00	0.56	0.31	o	o	0.50	4.23
Car R5	P	1.05	o	0.32	0.54	o	0.96	1.65	0.66	0.81	0.55	1.12	0.61	0.87	0.74	0.54	o	o	o	0.77	1.72
Car R6	D	0.13	0.04	0.03	0.02	o	0.02	0.03	0.09	0.06	0.03	*0.09*	0.02	0.01	0.02	*0.01*	o	*0.07*	o	0.04	0.12

11.3 Average result for the driver; o The driver did not drive this car; n/a Result is missing due to malfunctios; AVG Average

135 Result for the driver, one trip with regeneration event omitted; 135 Result for the driver, one trip only due to analyser fault; TA Type Approval

The average results for tested cars clearly show that we had a good choice of cars, because each of the emissions show quite wide spectrum of results. As for NOx, the range was from 9 mg/km up to nearly 140 mg/km, whereas for PN, the spread was even much more, as the low end was $0.01*10^{11}$#/km and the high end nearly $10*10^{11}$#/km, a range of almost 1 to 1000.

We then analysed the average emissions results of each driver compared to the average for that given car. That analysis is presented in Table 2.11, in similar fashion to Table 2.7. The colour coding is also similar, with green denoting values that were below the average for the given car, and red denoting the opposite, higher than average results. While viewing Table 2.11, we can see that for some drivers the colour stays the same with all cars, while for some drivers the colour changes from car to car.

Regarding CO_2, which actually is another embodiment of fuel consumption, the colour is predominantly the same for all cars. Drivers A, B, C, F, M and N have green (or greenish) colour for all cars, while drivers G, I and J have red (or reddish) colour for all cars. The rest of the drivers have both colours in their respective columns, meaning that with some cars their driving was efficient, but with other not so much. The difference between lowest and highest results was on average about 25 %.

Furthermore, regarding CO almost same applies, as drivers B, C and M maintain also green colour, but drivers A, F and N have at least one car, where they scored above average. On the other hand, drivers G, H, I and J had red colour on all the cars they drove, meaning that their driving style was producing high emissions.

However, with NOx no driver was able to have a "green" result, whereas no driver had the opposite, i.e. all "red" results. On the other hand, considering PN emissions, two drivers (C and L) reached "green" results on all cars they drove, but as with NOx, no driver had all "red" results.

Table 2.11: Driver-to-driver comparison of exhaust emissions for each test car

		TEST DRIVER POOL															AVG	TA	MIN	MAX	TOTAL
CO_2	Fuel	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	g/km			**AVG**	**26 %**
Car R1	P	-7 %	-13 %	-11 %	o	6 %	-5 %	11 %	9 %	o	22 %	2 %	-3 %	-2 %	0 %	5 %	120	99	-13 %	22 %	35 %
Car R2	D	-4 %	o	-6 %	3 %	-1 %	-5 %	5 %	-3 %	6 %	13 %	0 %	2 %	-2 %	-1 %	1 %	119	141	-6 %	13 %	19 %
Car R3	P	-4 %	-6 %	0 %	4 %	2 %	-5 %	o	9 %	13 %	5 %	5 %	1 %	-10 %	-11 %	7 %	118	115	-11 %	13 %	24 %
Car R4	P	-2 %	-3 %	-1 %	-0.4 %	-3 %	-1 %	2 %	o	16 %	1 %	-2 %	9 %	-3 %	o	-2 %	160	153	-10 %	16 %	26 %
Car R5	P	-8 %	o	-11 %	-5 %	o	-4 %	4 %	7 %	15 %	3 %	-2 %	14 %	-7 %	-3 %	5 %	139	117	-11 %	15 %	26 %
Car R6	D	-6 %	-12 %	-8 %	-6 %	o	-9 %	8 %	9 %	17 %	9 %	-5 %	-4 %	-11 %	-7 %	16 %	116	140	-12 %	17 %	29 %
Driver Average		-5 %	-9 %	-6 %	-1 %	1 %	-5 %	6 %	6 %	13 %	9 %	0 %	3 %	-6 %	-4 %	6 %					
CO	Fuel	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	mg/km			**AVG**	**188 %**
Car R1	P	5 %	-31 %	-31 %	o	-17 %	-8 %	64 %	5 %	o	37 %	49 %	-33 %	-22 %	6 %	-23 %	184.2	356	-33 %	64 %	96 %
Car R2	D	< all results missing due to analyser malfunction >																			
Car R3	P	190 %	-35 %	-52 %	-46 %	-14 %	204 %	o	68 %	37 %	-2 %	31 %	-81 %	-90 %	-76 %	-58 %	4.0	221	-90 %	204 %	294 %
Car R4	P	-8 %	-37 %	-24 %	-19 %	-16 %	-21 %	25 %	o	63 %	25 %	-9 %	-5 %	-25 %	o	-18 %	242.8	532	-37 %	70 %	106 %
Car R5	P	-26 %	o	-41 %	-15 %	o	-11.2 %	55 %	22 %	97 %	4 %	-2 %	-6 %	-29 %	-14 %	15 %	321.9	509	-49 %	97 %	146 %
Car R6	D	-92 %	-53 %	-94 %	-32 %	o	-52 %	173 %	118 %	-25 %	206 %	-93 %	-31 %	106 %	-23 %	-31 %	11.4	56	-94 %	206 %	299 %
Driver Average		14 %	-39 %	-48 %	-28 %	-16 %	22 %	79 %	53 %	43 %	54 %	-5 %	-31 %	-12 %	-27 %	-23 %					
NOx	Fuel	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	mg/km			**AVG**	**121 %**
Car R1	P	131 %	-21 %	-23 %	o	-47 %	-36 %	45 %	-36 %	o	-36 %	-1 %	1 %	-14 %	-2 %	-53 %	138.3	41.2	-53 %	131 %	184 %
Car R2	D	-23 %	o	-28 %	-18 %	-61 %	6 %	26.5 %	-7 %	83 %	107 %	-39 %	-8 %	-40 %	-3 %	-23 %	23.7	29.2	-61 %	107 %	167 %
Car R3	P	-10 %	-40 %	-17 %	13 %	4 %	39 %	o	13 %	-4 %	-16 %	5 %	-14 %	-9 %	25 %	-28 %	10.3	34.1	-40 %	40 %	81 %
Car R4	P	-18 %	0 %	-60 %	10 %	-38 %	-16 %	17 %	o	27 %	16 %	8 %	3 %	42 %	o	38 %	9.2	17.5	-60 %	42 %	102 %
Car R5	P	24 %	o	45 %	-4 %	o	-38 %	-25 %	-44 %	-5 %	-34 %	57 %	81 %	-24 %	-7 %	14 %	17.7	14.2	-44 %	81 %	125 %
Car R6	D	-4 %	25 %	-33 %	-13 %	o	-3 %	1 %	34 %	-5 %	-2 %	36 %	0 %	-24 %	-33 %	15 %	44.9	34.9	-33 %	36 %	69 %
Driver Average		17 %	-9 %	-19 %	-2 %	-36 %	-8 %	13 %	-8 %	19 %	6 %	11 %	11 %	-11 %	-4 %	-6 %					
PN	Fuel	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	10^{11}#/km			**AVG**	**190 %**
Car R1	P	23 %	-8 %	-32 %	o	-10 %	-16 %	18 %	18 %	o	18 %	3 %	-19 %	1 %	18 %	-2 %	9.75	18.4	-32 %	23 %	55 %
Car R2	D	278 %	o	o	-12 %	-23 %	-34 %	n/a	-35 %	-12 %	-20 %	-33 %	o	o	-22 %	-12 %	0.01	0.02	-38 %	278 %	316 %
Car R3	P	21 %	-11 %	-4 %	16 %	20 %	12 %	o	1 %	48 %	82 %	-5 %	-29 %	-44 %	-22 %	-39 %	0.32	1.08	-44 %	82 %	126 %
Car R4	P	-47 %	-36 %	-83 %	2 %	-33 %	23 %	59 %	o	131 %	65 %	-51 %	-22 %	19 %		12 %	0.50	4.23	-83 %	131 %	214 %
Car R5	P	36 %	o	-59 %	-31 %	o	25 %	114 %	-15 %	4 %	-29 %	45 %	-21 %	13 %	-4 %	-30 %	0.77	1.72	-59 %	114 %	173 %
Car R6	D	188 %	-16 %	-42 %	-63 %	o	-50 %	-31 %	110 %	35 %	-28 %	105 %	-65 %	-69 %	-54 %	-70 %	0.04	0.12	-70 %	188 %	258 %
Driver Average		83 %	-18 %	-44 %	-17 %	-12 %	-7 %	40 %	16 %	41 %	15 %	11 %	-31 %	-16 %	-17 %	-24 %					

n %	Results is from one trip only, due to abnormality caused by DPF regeneration event
o	Driver did not drive this car
Fuel	P=petrol, D=diesel
-44 %	Result is below average
81 %	Result is above average
AVG	Average for the car
TA	Type Approval result for this car
MIN	Smallest deviation from average
MAX	Largest deviation from average
AVG	Average for all cars

Finally, a composite score was calculated that included the trip-related score, fuel economy score, and the aggregated emissions score. These are presented for each driver in Table 2.12. For each driver, an emissions score was calculated as a non-weighted average of CO, NOx and PN scores. CO_2 was not accounted, as it is already included in the Fuel Economy score presented in Table 2.8.

Table 2.12: Combined driver scores for Trip, Fuel Economy and Exhaust Emissions

	TEST DRIVER POOL														
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
DRIVING	-1 %	-7 %	-4 %	2 %	2 %	-1 %	4 %	4 %	4 %	6 %	2 %	-3 %	-2 %	-3 %	3 %
CO_2	-5 %	-9 %	-6 %	-1 %	1 %	-5 %	6 %	6 %	13 %	9 %	0 %	3 %	-6 %	-4 %	6 %
CO/NOx/PN	38 %	-22 %	-37 %	-16 %	-21 %	2 %	44 %	20 %	35 %	25 %	6 %	-17 %	-13 %	-16 %	-18 %
CO_2/CO/NOx/PN	16 %	-15 %	-22 %	-8 %	-10 %	-1 %	25 %	13 %	24 %	17 %	3 %	-7 %	-10 %	-10 %	-6 %
RANKING	12	2	1	6	3	9	15	11	14	13	10	7	5	4	8

As Table 2.12 shows, the driver pool had some drivers (B, C, M and N) that could be regarded as “talented low emissions drivers”, because all of their scores were below average, hence marked with green colour, but also those (G, H, I and J) that were the opposite end of the spectrum, and marked with red colour. Of course, there were also intermediates, and a few that scored well on fuel economy, but not on emissions, and a few also vice versa, i.e. good emissions, but higher than average fuel consumption. This scoring shows that there is a definite difference in emissions regarding how the car is driven, even with cars that have the latest and most sophisticated engine management and emissions control systems. The scoring also gives us a hint that we should inspect the driving parameters recorded for both ends of the spectrum to find the root causes for these scores.

2.9 Results on second-by-second level

In this chapter, results from the PEMS measurements are presented as a combined plot of each of the drivers' individual test runs. The graphs are supposed to portray the diversity of the driving patterns that – based on the high-level analysis – still seem to affix to the driver's driving style.

The graphs are presented here only for car R1, and include the same driving parameters and emissions listed in Table 2.5 and Table 2.9, but similar graphs for the rest of the tested cars are included in Appendix 1.

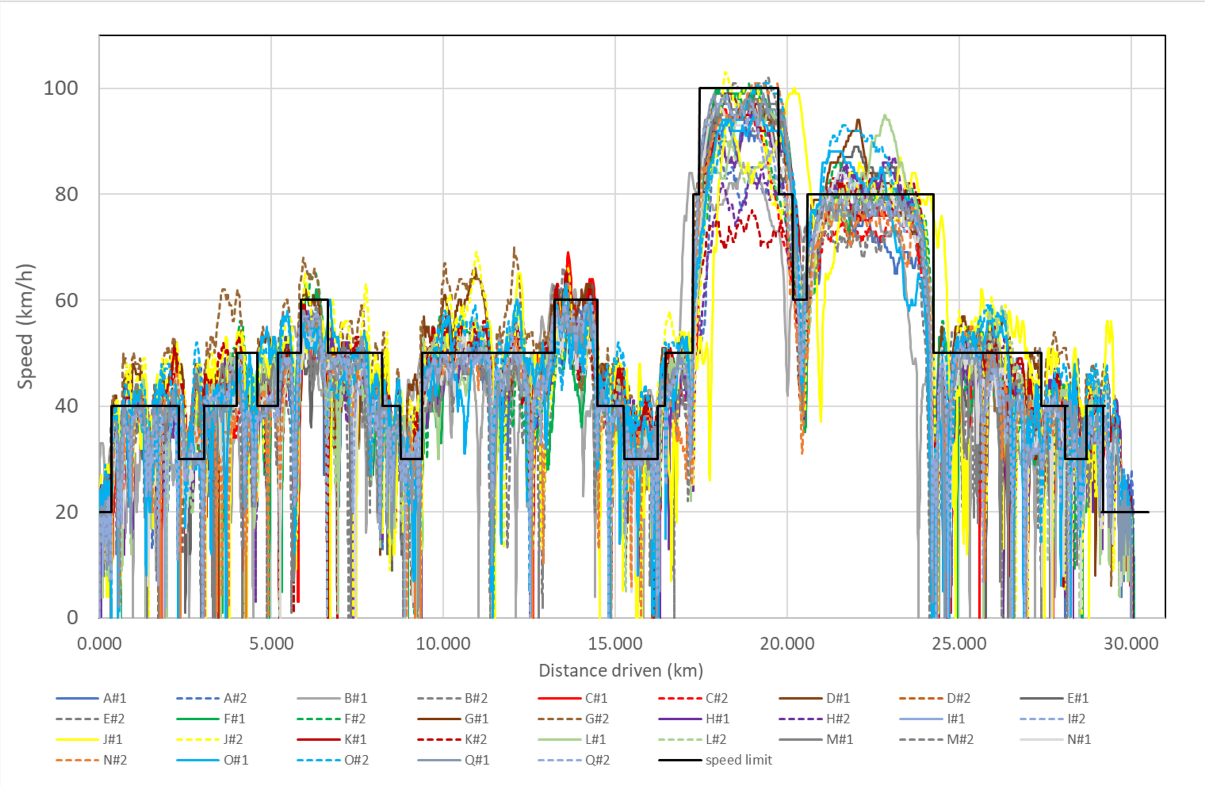


Figure 2-8: Speed vs. driven distance for all drivers and trips for car R1

Regarding speed (Figure 2-8), the pattern loosely follows the speed limit imposed on that given part of the route, but even so, we can see a considerable difference between drivers. Over the street section, there are also differences in the number of stops. This is partially not dependent on driver, as over the course there were many traffic lights and all sort of similar features that made some drivers to stop, while the others did not, irrespectively of their driving pattern. However, we know that some drivers are better in perceiving the traffic environment than others, and can keep the car in more constant movement, and avoiding unnecessary stops and subsequent re-accelerations.

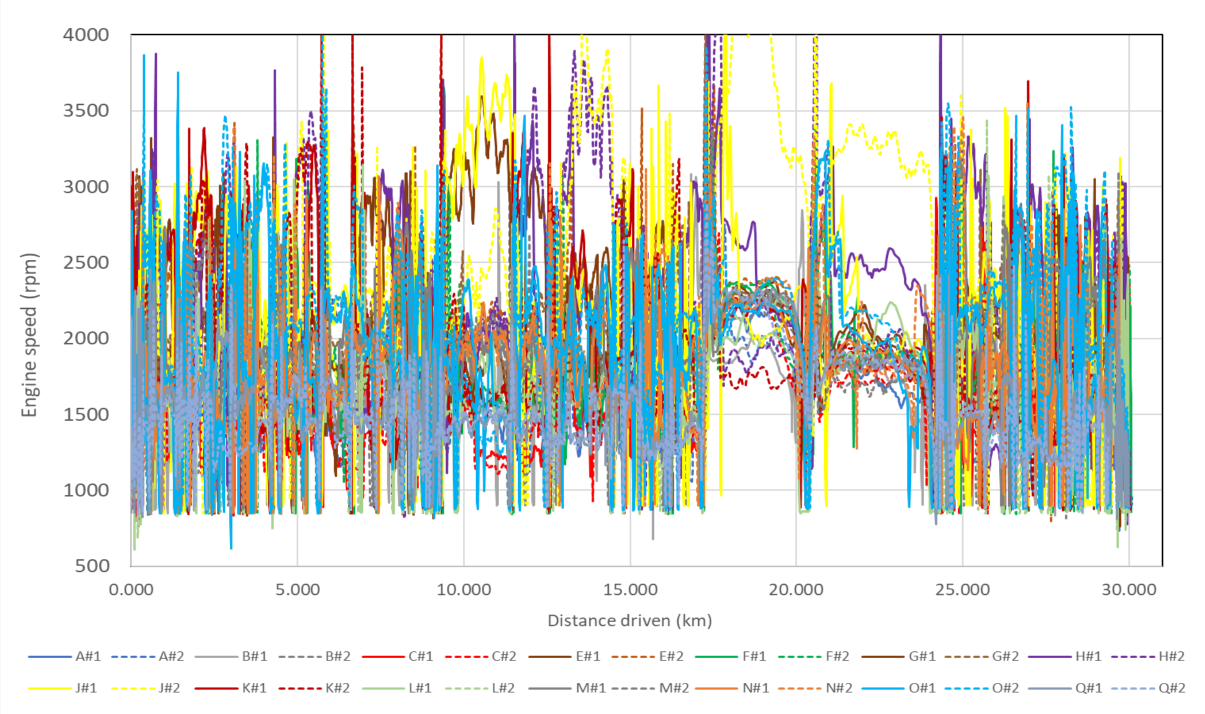


Figure 2-9: Engine speed vs. driven distance for all drivers and trips for car R1

Regarding engine speed, there ae clear differences between drivers especially over the high-speed sections of the route, presenting the fact that drivers clearly did use different gears for those parts.

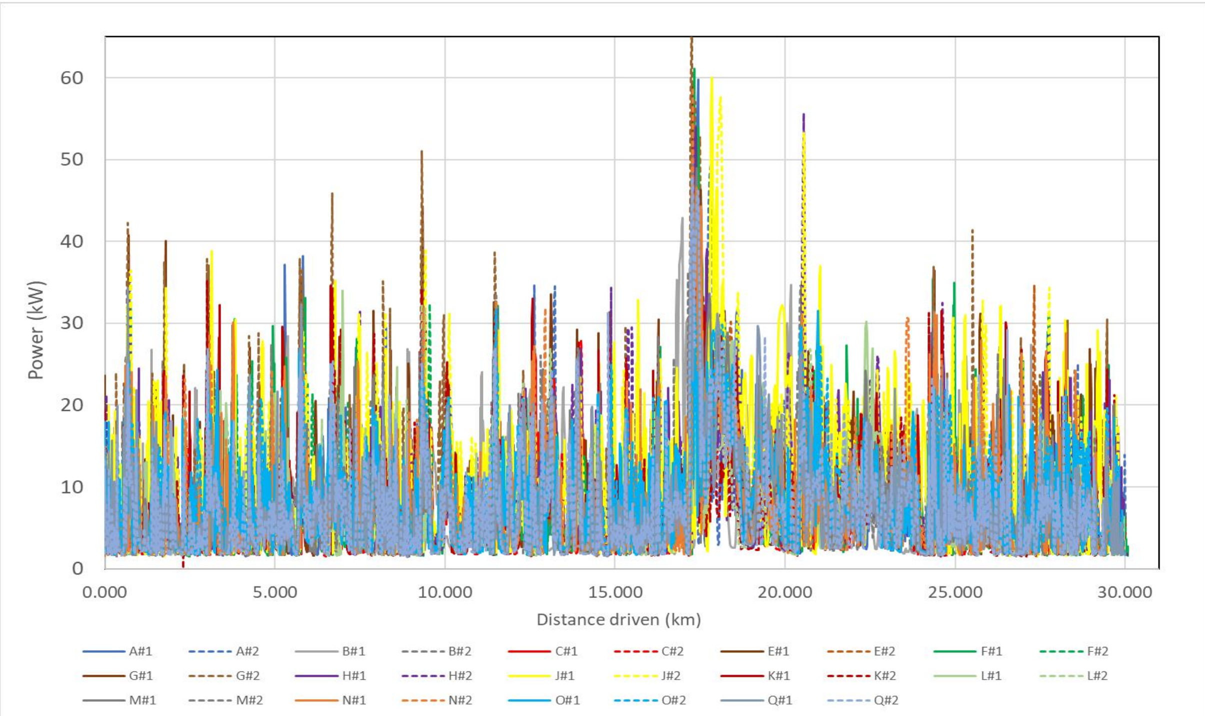


Figure 2-10: Engine power vs. driven distance for all drivers and trips for car R1

What comes to engine power, its use is quite "peaky", with clear spikes at places were stronger accelerations are imposed, like entering the motorway at about 17.5 km. However, some drivers seem to use more power than the others even in other places, too.

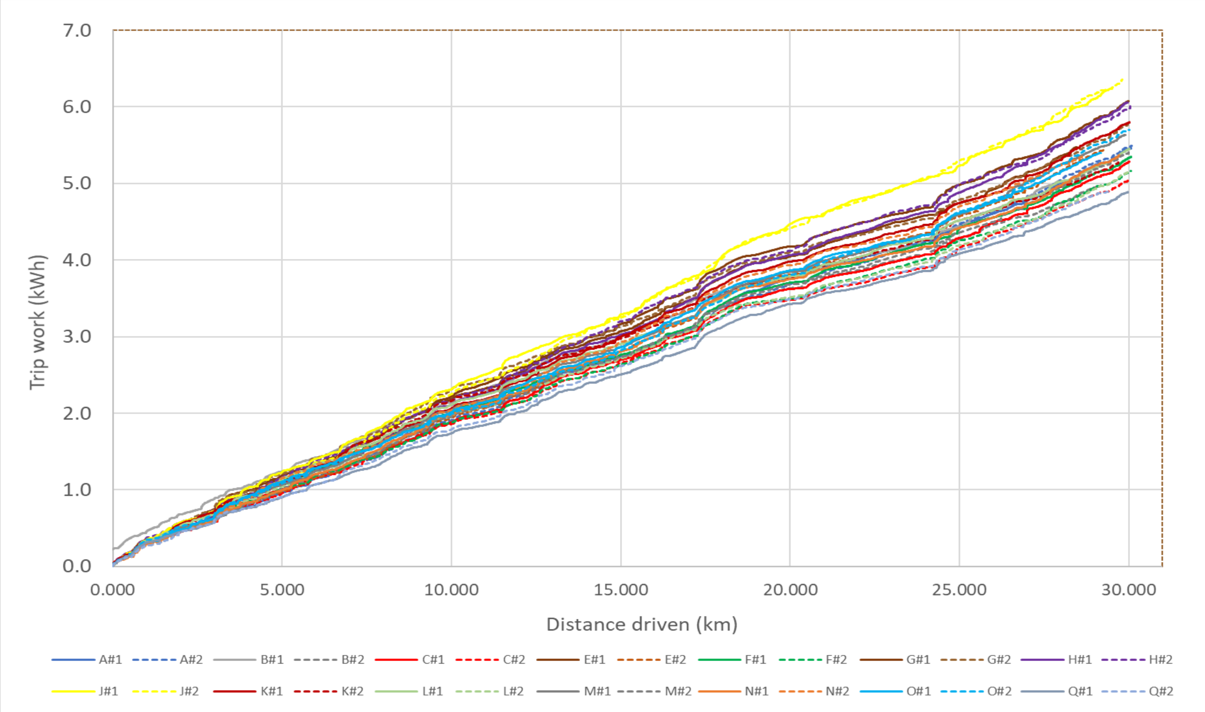


Figure 2-11: Cumulated trip work vs. driven distance for all drivers and trips for car R1

When reviewing the plots for cumulative work, we can see how the accelerations and power peaks slowly differentiate the drivers from each other, even if the differences in total accumulated power are not that high, in the order of some 20% between the lowest and highest result.

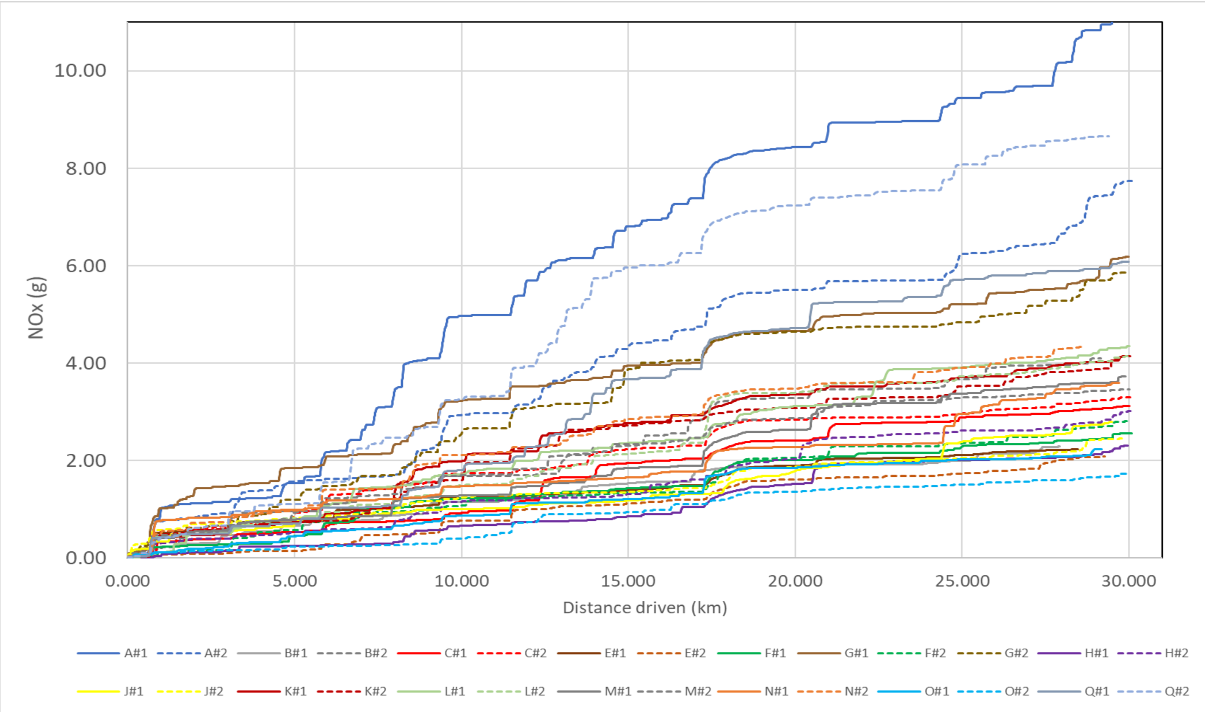


Figure 2-12: Cumulated NOx vs. driven distance for all drivers and trips for car R1

Regarding accumulation of NOx, the differences between drivers are quite distinct, and with some drivers, the two subsequent rides are quite different, even if cannot be seen very well in this graph.

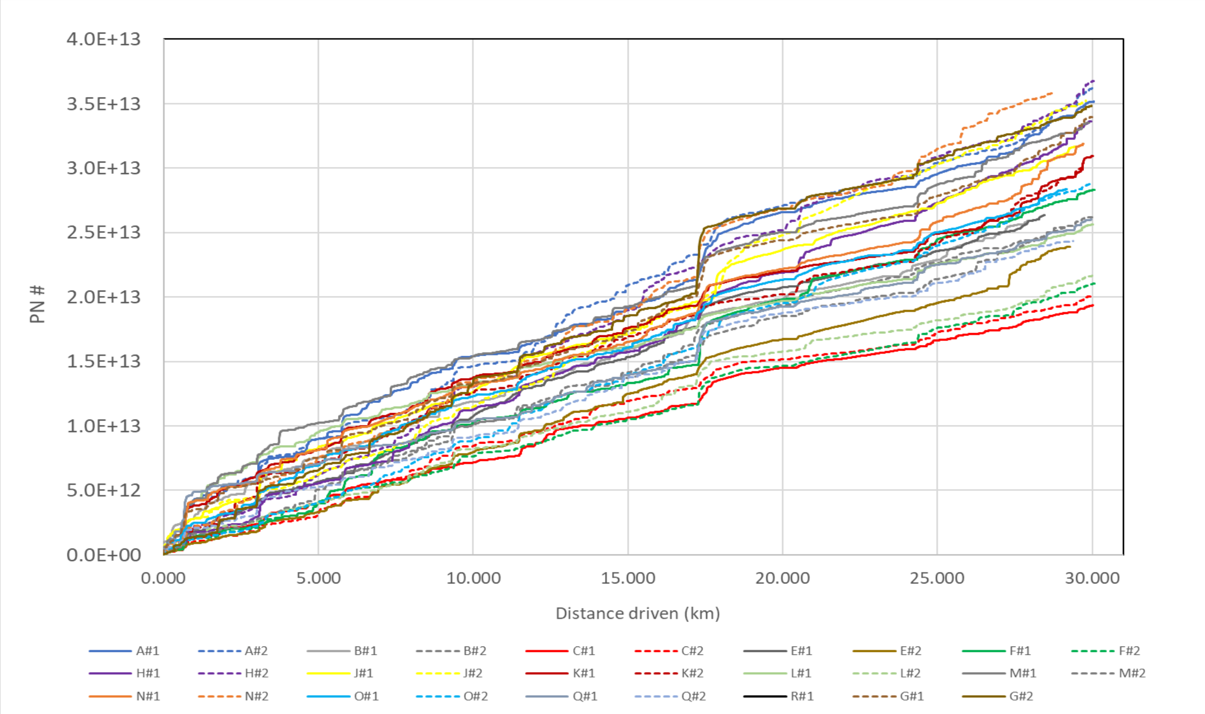


Figure 2-13: Cumulated PN vs. driven distance for all drivers and their for car R1

Coming to PN, the spread in results are not as large as with NOx, as the highest is only about twice of the lowest figure, whereas with NOx, this ratio was close to 1:6. However, we can see that the critical point in the route regarding particulate emissions was the acceleration over the ramp to the motorway, which occurs at about 17.5 km mark, and a clear upward push is seen in almost all traces. This is probably accentuated by the fact that this particular car did not have any GPF, and its PN emissions were by far the largest of the pool of cars tested in this exercise.

Furthermore, when viewing the Figures 2-8 to 2-13, it is apparent that when plotted in the same graph, the individual driving style and resulting emissions performance for different drivers cannot be recognised, and the "bandwidth" becomes quite large. However, if plots for three drivers that have distinctly different driving styles are separated, the representation becomes quite clear. Figure 2-14 shows this kind of comparison between drivers A, C and J, that represent opposite ends of the pool: driver C had the best combination between trip-related parameters and emissions output, driver A scored well for trip parameters and fuel use, but presented high NOx, while driver J had the least economical driving style, and also quite high emissions over all tested cars.

While the drivers' speed vs. driven distance profiles are not that different, it seems that drivers A and C managed to drive the route with fewer stops than driver J, who also used much higher engine speeds, apparently by choosing a lower gear. This resulted in higher power use, and also higher accumulated work over the trip, which was almost directly replicated in higher accumulated CO_2 emissions. Even if driver C seemed to have more consistent driving profile, the NOx output between the two test runs differed more for driver C than for driver J. However, driver A presented the highest NOx output, and also quite large difference between the first and the second test run. Again, regarding PN emissions, all drivers had quite characteristic, but different performances, as driver C presented the lowest result for that given car, while the results for drivers A and J were amongst the highest.

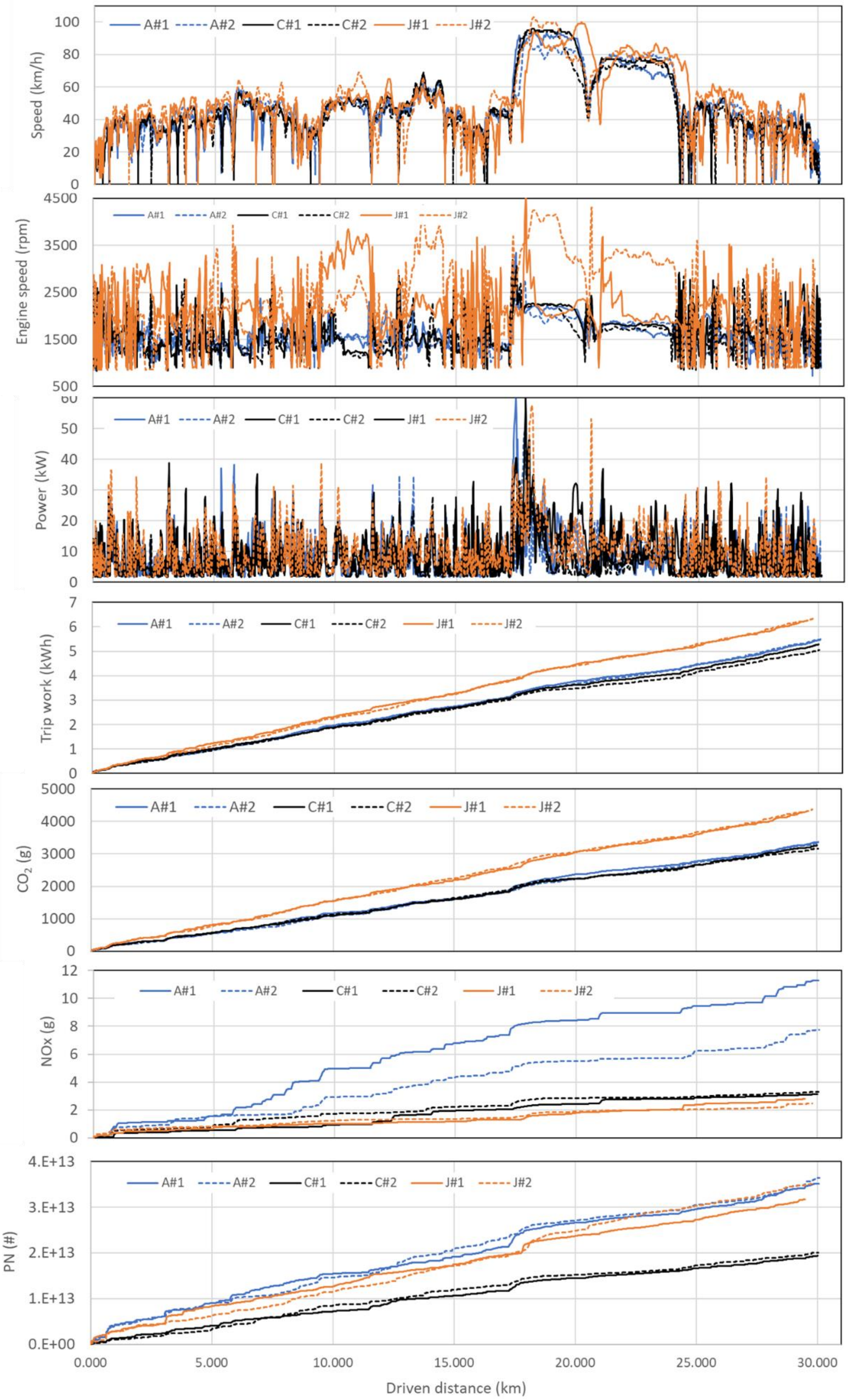


Figure 2-14: Speed, engine speed, power, work, CO_2, NOx and PN as a function of distance for drivers A, C and J with car R1

3. Brakes emission methodology and measurements

This task plans, carries out and analyses the brake emission campaign, preliminary setting up the dynamometric laboratory test set-up facility. The latest version of the common inter-laboratory methodology to independently measure non-exhaust brake-related emissions in terms of particle matter (PM) and particle number (PN), developed in the PMP Particle Measurement Programme Informal Working Group (PMP-IWG) under the UNECE (United Nations Economic Council for Europe) umbrella, was implemented in the Brembo brake dynamometer test setup, and it was one of the test set-ups that have been used to develop such a methodology. The complete information about the test setup and the reference testing cycle are collected into the GRPE-81-12 informal document [1].

A reference cycle (WLTP-brake) consisting in 303 braking events was applied in order to rank each event as a function of their PM/PN emissions. While a similar methodology was developed in the REBRAKE and LOWBRASYS projects, and applied to a passenger car, some additional tests were needed to explore the emission variability as a result of different driving behaviours, road conditions, vehicles and braking system materials.

Mathematical description to cover all the braking manoeuvres that the driver can make while driving/braking was created using these PM/PN test results. Proof and validation of this mathematical model in a few selected cases was done at the brake dynamometer level using real driving cycles and different driver profiles.

3.1 Brake emission measurements

The measurement of brake emissions is a widely discussed topic within the PMP-IWG. The experimental data acquired during the MODALES Project have been collected according to the most recent guidelines defined by the group, at the time of the tests.

The tests were performed on a dynamometric bench. These types of tests are widely used in the field of the characterization of the braking components, they are laboratory scale tests, performed in particularly controlled conditions. These tests have been selected by the PMP group to guarantee the best reproducibility and repeatability of the emission measurement. In order to fulfil the repeatability and reproducibility requirements, a fully enclosed brake inertia dynamometer has been selected as the reference testing system for the emission measurement. The schematic representation of the brake enclosure is depicted in Figure 3-1.

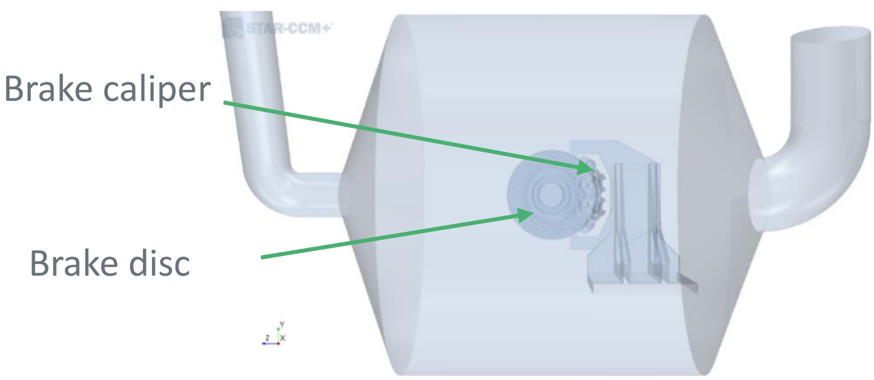


Figure 3-1: Brake enclosure used for the dyno-bench tests

As can be noted from Figure 3-1, this close enclosure hosts the braking components and prevents the particle losses over the entire sampling and measurement line. From Figure 3-2 it can be noted that a clean air flux is entering the brake enclosure; it has a twofold aim:

- it guarantees a proper cooling at the braking components during the testing cycle;
- it brings the particle generated at the rubbing interface to the particle measurement apparatuses.

The inlet air flow passes into a high efficiency HEPA H-13 filter with a filtration efficiency > 99.95%. The GRPE-81-12 informal document [1] provides indication about the cooling flow rate to be adopted during tests, as the disc temperature has to comply with a pre-set temperature window, generated on the basis of disc temperature measurements during proving ground tests.

The emission measurement was carried out by means of different sampling probes connected to the measuring instruments. Each probe is equipped with a dedicated nozzle to guarantee the isokinetic sampling; their diameter is selected according to the velocity of the airflow in the exiting duct of the brake enclosure that has to be equal to the air speed at the nozzles. The isokinetic sampling is fundamental to prevent flow distortion and to minimize the particle losses in the sampling probes. Figure 3-2 shows the geometry of the brake enclosure and also the position of the sampling plane.

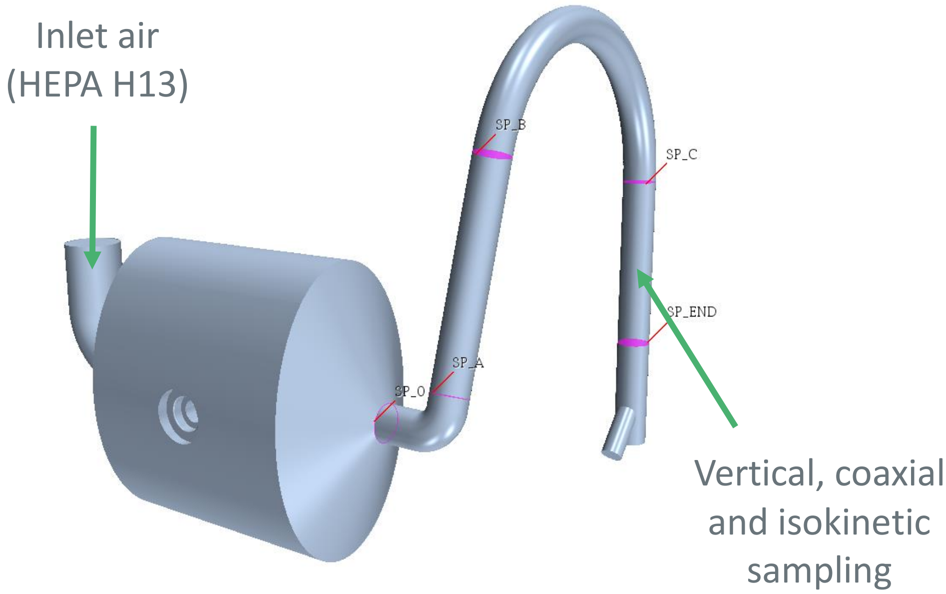


Figure 3-2: Brake enclosure and sampling plane

The particles have been collected and measured by different apparatuses:

- Dekati PM_{10} impactor, it is the reference instrument for the calculation of the emitted particle mass. It is a mechanical impactor that collects particles onto three collection substrates and a high efficiency filter. The collection substrates and the filter are weighed before and after the test to determine the amount of particles collected (in mg);
- Dekati ELPI+, it is an electrical low-pressure impactor that measures real time the number and the mass of the emitted particles. It collects the particles onto fourteen collection substrates;
- TSI 3775 condensation particle counter (CPC), it is the reference instrument for the measure of an instrument that measures real time the number of the emitted particles.

A schematic representation of the experimental apparatuses used is depicted in Figure 3.3.

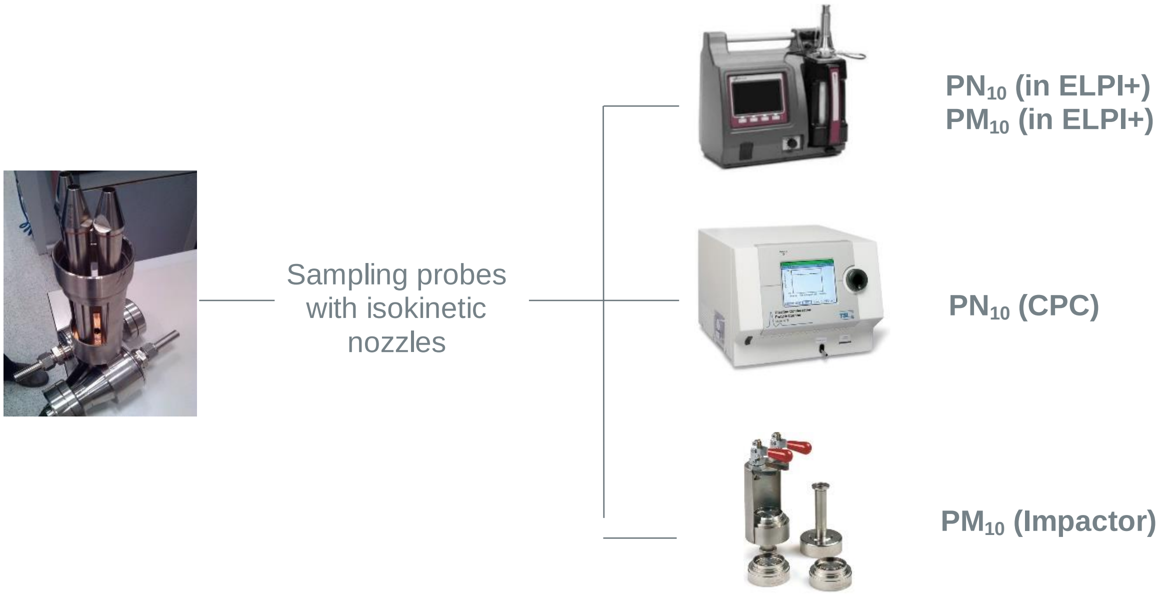
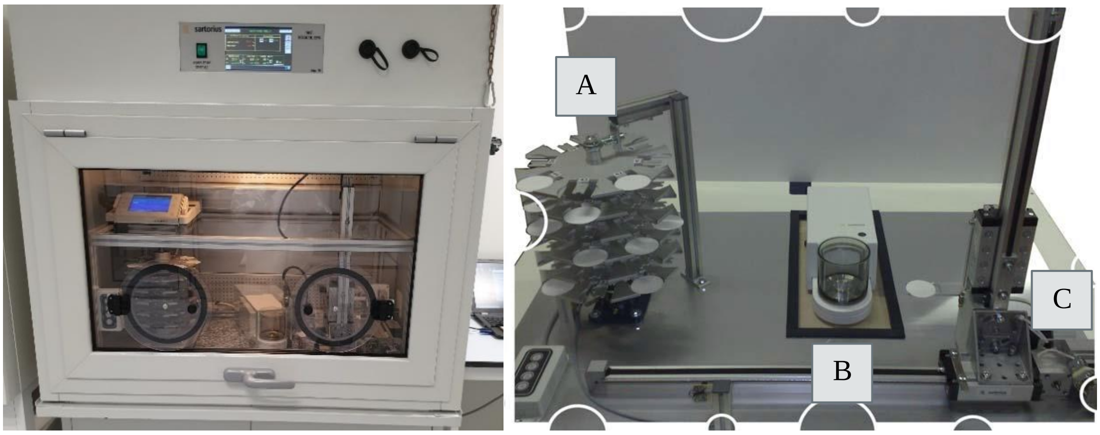


Figure 3-3: Experimental apparatuses used to sample and measure the emitted particles

As mentioned above, the collection substrate(s) of the PM_{10} impactor were weighed before and after each test, to calculate the amount of particle collected, in mg. The analytical microbalance used for the filter and collection substrate weighing has a sensitivity of 0.1 µg. This particularly high sensitivity requires some precautions to generate accurate and reliable data:

- A charge neutralizer is located close to the balance in order to neutralize the electrostatic charge of the filters and collection substrates;
- An automated system brings the filters and collection substrate from a stocking tower to the balance, in this way the errors due to their manual handling are avoided;
- The weighing system is placed inside a particle free and conditioned glovebox. The conditioning conditions are in accordance to the regulations no. 49 and 83 [2], [3]. The substrates and the filters are kept at a temperature of 22 ± 1 °C and at 9.5 ± 1 °C dew point for at least 24 hours before the weighing operation.

Figure 3-4 shows the particle free glovebox and the automated weighing system used for the weighing of the filters and substrates.



(a) (b)

Figure 3-4: Particle-free, conditioned glovebox and automated weighing system

The label A of Figure 3-4 refers to the rotating tower where the filters and the collection substrates are placed for the conditioning, B marks the analytical microbalance and C is the automated arm that picks up the filters from A and brings them to the balance B for weighing, subsequently returning them afterwards.

In order to avoid any contamination of the substrates and filters, the glove box is located in a certified ISO6 clean room (according to ISO14644-1 standard). All the instrument set-up operations have been performed inside the clean room. Figure 3-5 shows the particle-free glovebox inside the cleanroom.

Figure 3-5: ISO 6 clean room for filter, substrate and sampling device preparation

3.2 Testing cycle

In this section, some considerations about the testing cycle are summarized.

In order to choose a testing cycle that is most representative of real driving conditions, Mathissen et al. [4], developed a novel cycle that relied on the WLTP database. This database includes the data of more than 750 000 km vehicles, from several regions around the world. The cycle was validated using proving ground and extensive dyno-bench testing at several facilities around the world. As stated before, the laboratory-scale testing ensures a particularly suited tool to achieve significant results that are not affected from the air and particle dynamics related to the vehicle under testing, environmental dilution of the particles and other aerosol interaction with the environment.

Due to the high number of data included in the WLTP database, the reference testing cycle used for the investigation of the average braking behaviour of the drivers was the novel WLTP-Brake cycle. The reference vehicle used to study the emission of the braking components, was a C-segment European passenger car, equipped with traditional pearlitic gray cast iron rotors and a low steel friction material.

Since the aim of T3.2 was to detect the role of the drivers and their driving behaviours on brake emissions, some modifications have been applied to this reference cycle in order to reproduce a more conservative driving and braking. The reference cycle has been analysed and some of its braking events have been modified accordingly to the guidelines for low emission driving, as reported in D5.1. In particular, the simulated vehicle decelerations and the initial braking speed of the most demanding stops have been reduced. As mentioned above, all these modifications have been selected in order to simulate a higher attention of driver to the traffic situations and thus a more conservative driving behaviour. Moreover, with the aim of replicating the same trip, the total length travelled by the vehicle along the testing cycle and the number of the braking events have kept equal to the reference WLTP-Brake. The simulated speed profiles of the vehicle during the reference and modified WLTP-Brake cycles are reported in Figure 3-6.

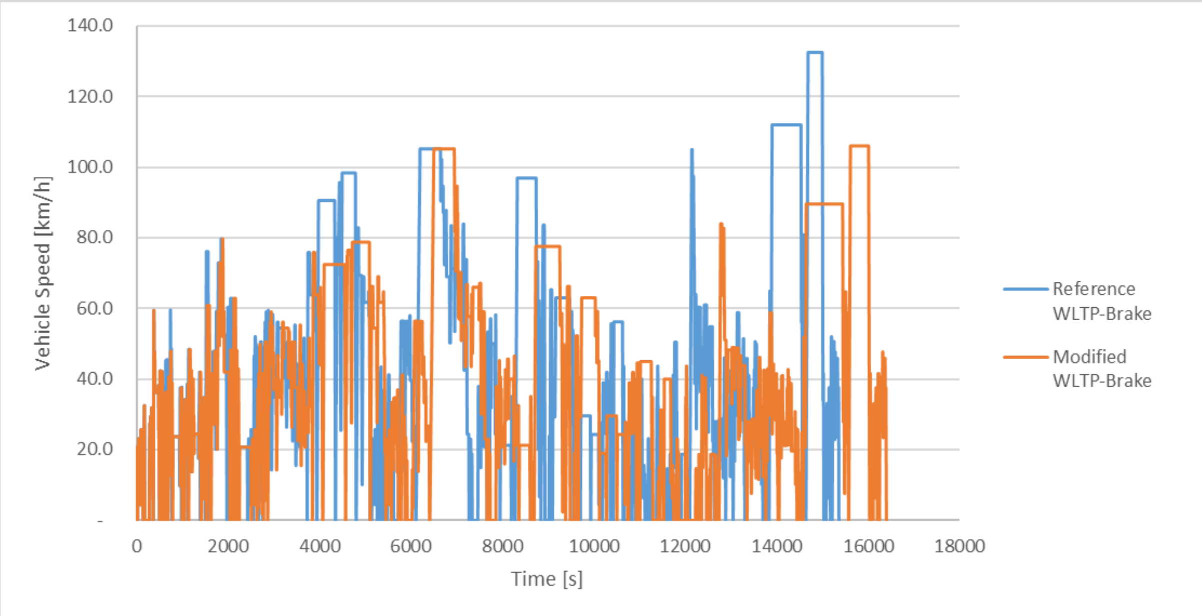


Figure 3-6: Comparison of the speed profile during the reference and modified WLTP-brake testing cycle

As can be noted from Figure 3-6, the overall testing time is increased of roughly 17 minutes passing from the reference to the modified WLTP-Brake cycle. This increase in time is related to the lower average brake speed achieved with the "smoothening" of the driver behaviour. The main parameters of the two testing cycles are resumed in Table 3.1.

Table 3.1: Parameters of the two testing cycles used to detect the brake emissions

Parameter	Reference WLTP-Brake Cycle	Modified WLTP-Brake Cycle
Average brake speed [km h^{-1}]	43.7	41.0
Deceleration range [m s^{-2}]	0.49-2.18	0.49-2.18
Average deceleration [m s^{-2}]	0.97	0.82
Initial brake temperature [°C]	40 ≤ T ≤ 175	40 ≤ T ≤ 115
Travelled distance [km]	192	192
Number of braking events	303	303

As can be noted from the deceleration range, the maximum deceleration has not been modified because it was assumed that this value is representative of an emergency braking event that cannot be modified for safety reasons.

3.3 Results of the emission tests

The main aim of the modified cycle is to reduce the kinetic energy dissipated by the brakes. Figure 3-7 depicts the initial brake speed as a function of the different braking events, or stop number, and Figures 3-8, 3-9 and 3-10, of the reference WLTP-Brake and the modified WLTP-Brake.

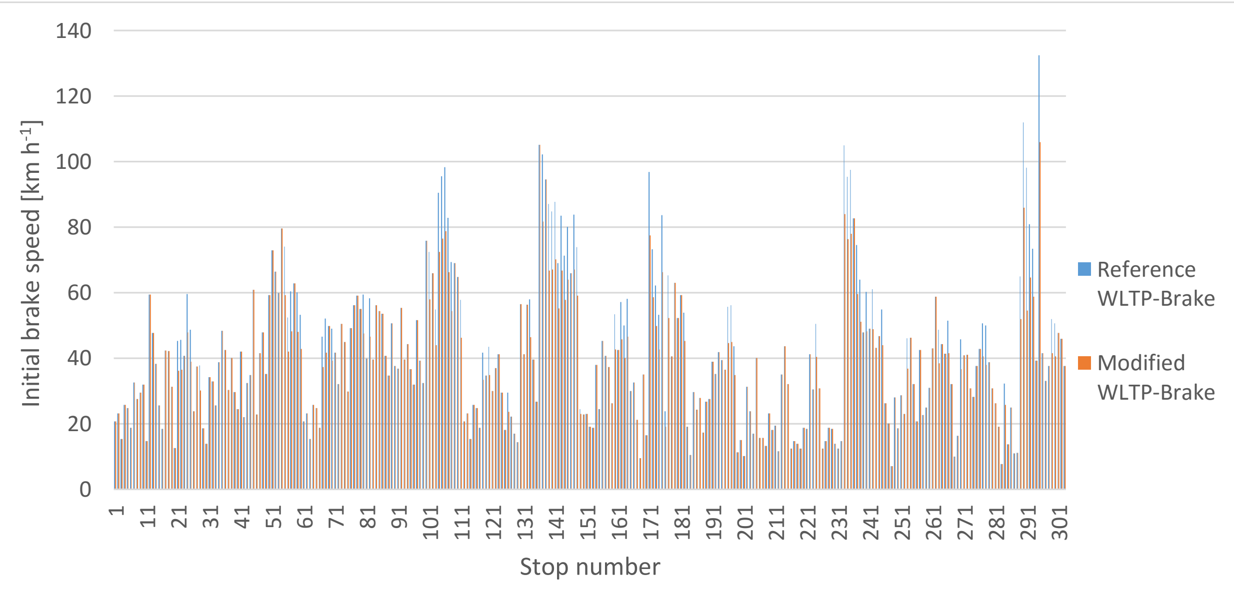


Figure 3-7: Comparison of the vehicle speed during the reference and modified WLTP-brake testing cycle

As can be noted from Figure 3-7, the algorithm created and based on the considerations in D5.1, identified 91 braking events to be modified, corresponding to the 30% of the overall 303 events found in the reference WLTP-Brake cycle. The overall kinetic energy reduction achieved by applying these modifications was equal to the 22%, for a better identification of the variation in the kinetic energy and power dissipated by brakes during the different stops of the testing cycle, see Figure 3-8.

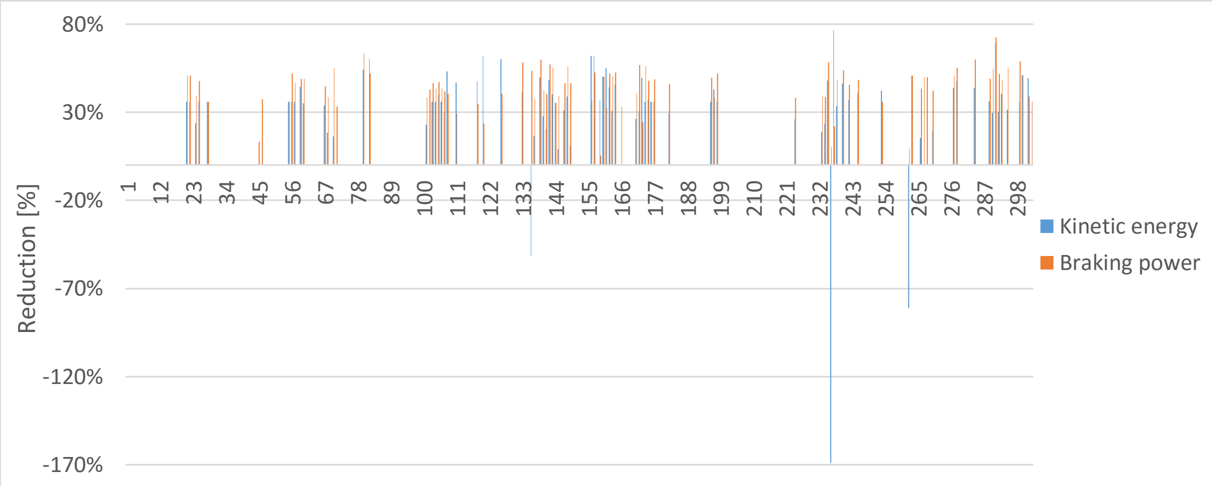


Figure 3-8: Kinetic energy and braking power variation with respect the reference WLTP-brake cycle

As can be noted from Figure 3-8, the braking events with a positive reduction in the kinetic energy are associated with a reduction in the initial brake speed. Some stops, i.e. the stop number 136, 236 and 262, that showed a negative reduction in the kinetic energy are related to the modification of the in-stop deceleration. In order to keep the vehicle travelled distance constant, the reduction in the in-stop deceleration led to a lower final brake speed and to higher in stop time. Although the apparent increase in the kinetic energy dissipated by brakes during the stops mentioned above, the braking power (energy dissipated per second) is always lower, leading to a smoother and more gradual thermal input of the system and thus to lower disc temperatures.

The lower energy and power dissipated during braking resulted in a lower disc temperature, as seen in Figure 3-9.

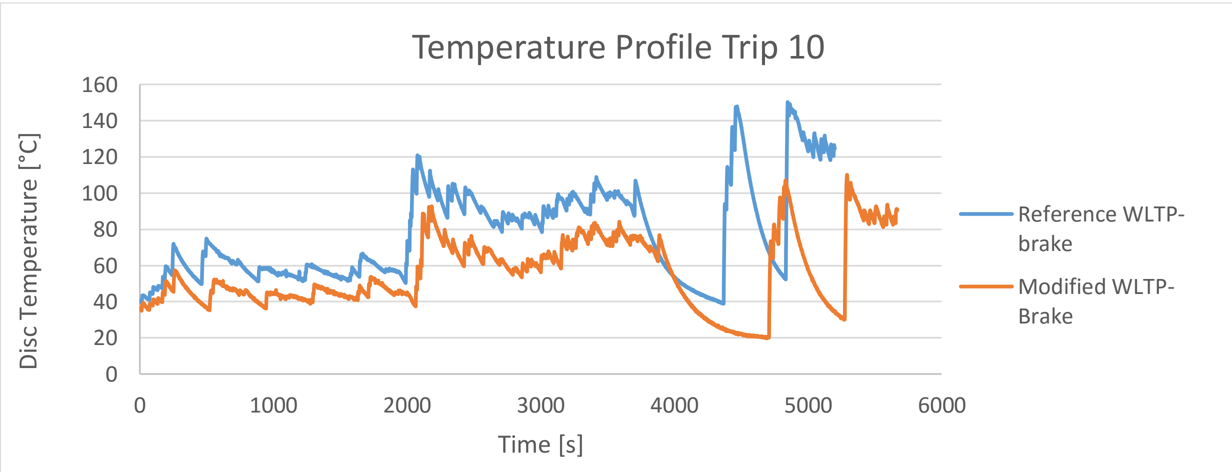


Figure 3-9: Disc temperature profile during Trip 10 of the reference and modified WLTP-Brake cycle

As known from the literature and widely discussed in D2.2 and 5.1, the lower disc temperatures led to lower PM and PN emissions (Figure 3-10 and 3-11). The labels PM_{10}, $PM_{2.5}$ and PM_1 refer to particles with an aerodynamic diameter lower than 10, 2.5 and 1 µm respectively.

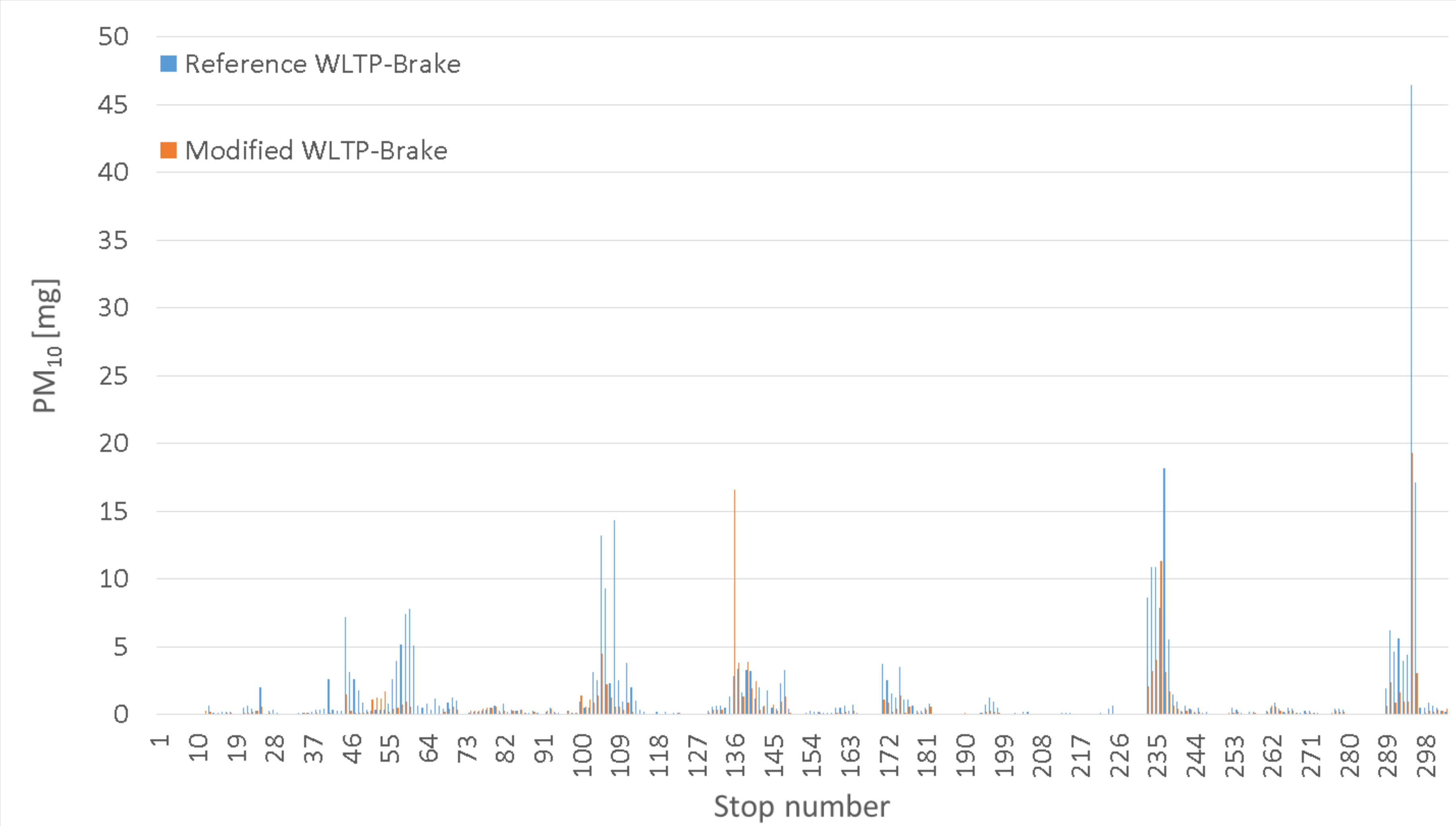


Figure 3-10: PM_{10} emissions as a function of the stop number

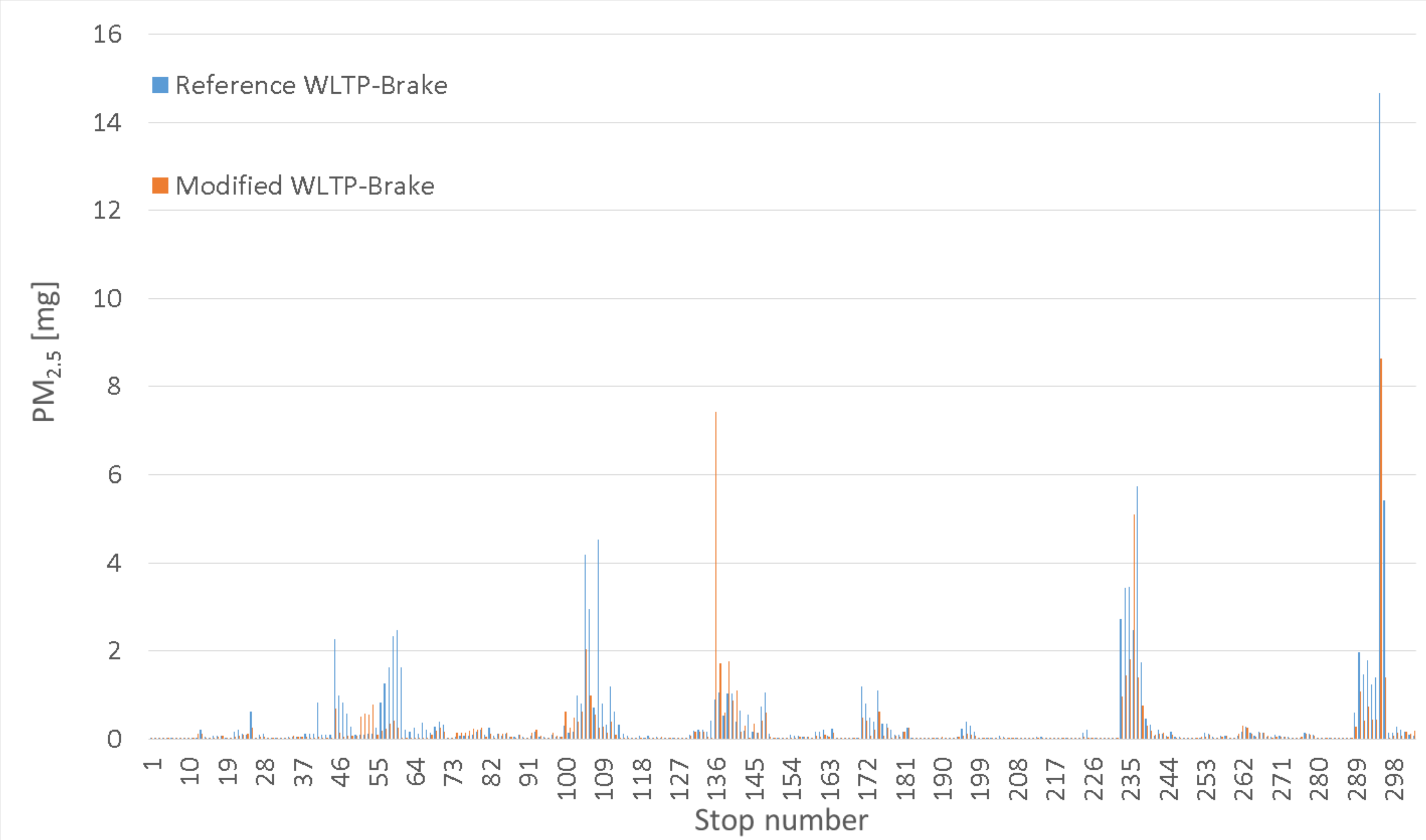


Figure 3-11: $PM_{2.5}$ emissions as a function of the stop number

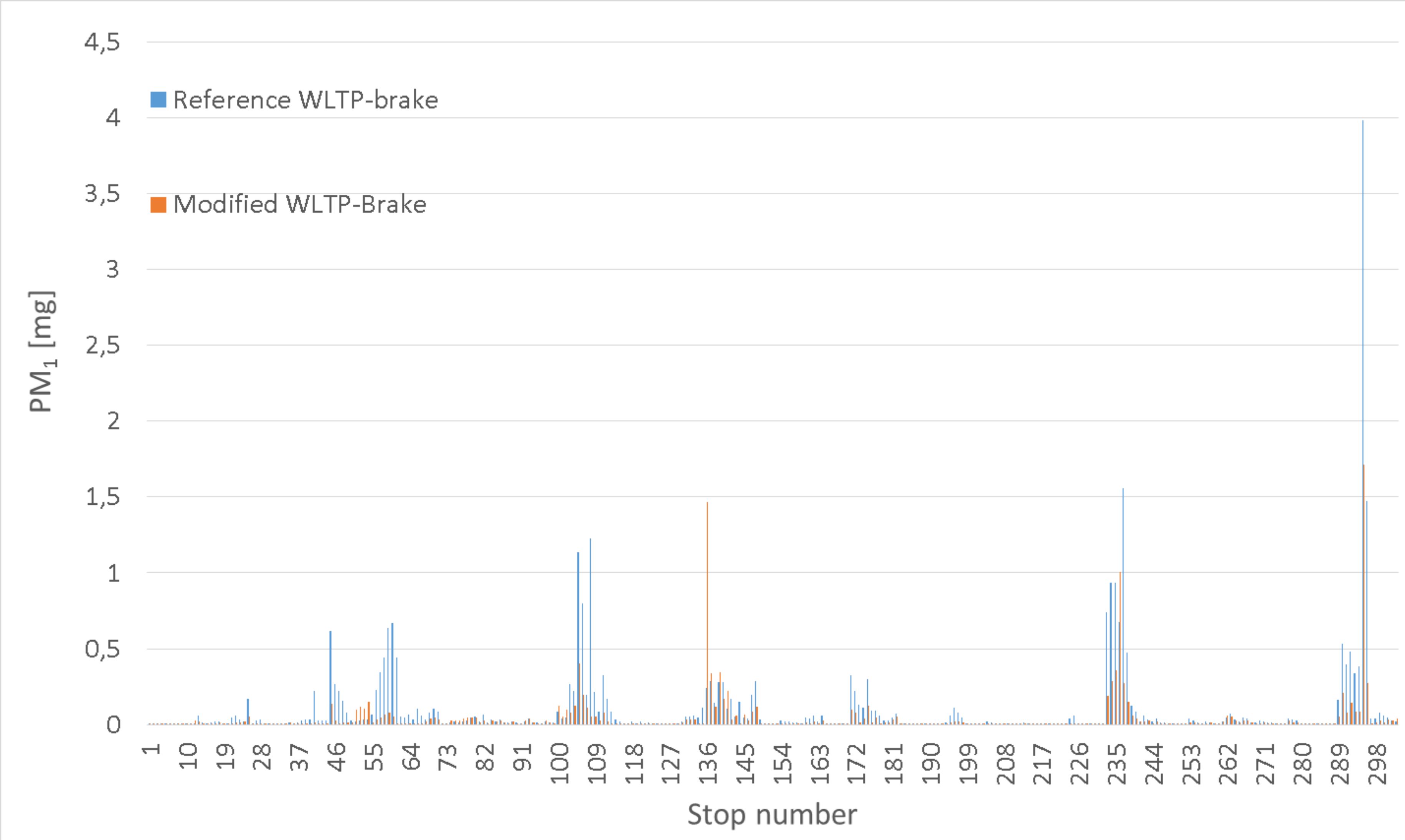


Figure 3-12: PM_1 emissions as a function of the stop number

These Figures show that the modifications of the testing cycle were able to reduce the mass of the emitted particles in all the measured dimensional ranges (10, 2.5 and 1 µm) for a high number of braking events. Nevertheless, the effectiveness of these modifications, some emission peaks are higher in the modified WLTP-Brake; this behaviour can be ascribed at the high complexity of the emission phenomenon and of the friction material formulations. These materials are made of more than 20 constituents that can affect in different ways the emission behaviour.

During the data elaboration the "particle shower" effect, that is the release of particles due to some changes in the disc rotating speed, has been taken into account to avoid underestimation of the emitted mass per braking event.

The particle number is shown in Figure 3-13, the number emission per stop is consistent with the emitted particle mass. From Figures 3-10, 3-11 and 3-12 it can be noted that the maximum emission peaks are associated with the braking events that experienced the highest disc temperature. This fact is a further confirmation of the particularly strong effect of the disc temperature on the particle emission.

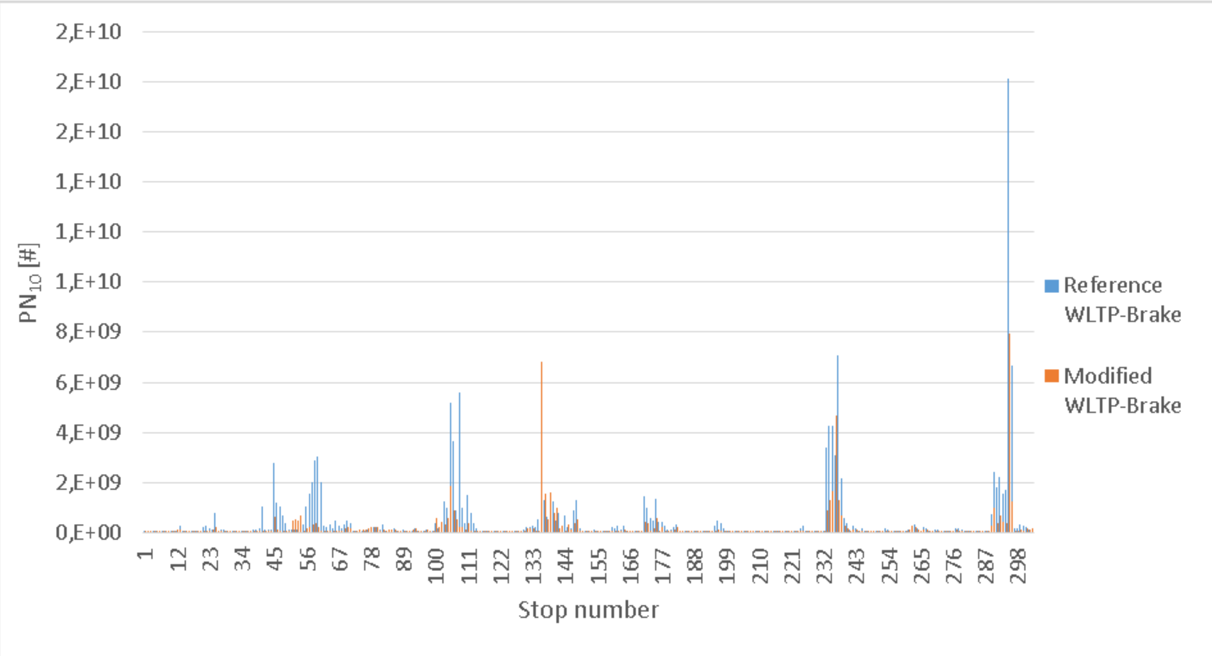
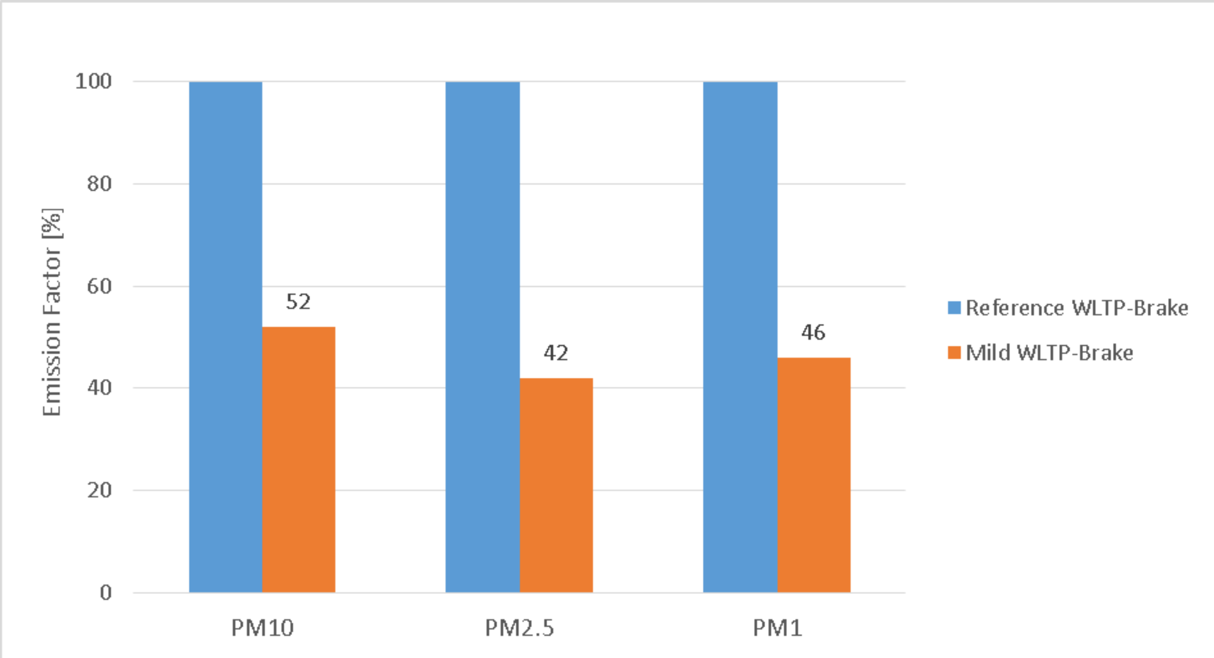


Figure 3-13: PN_{10} emissions as a function of the stop number

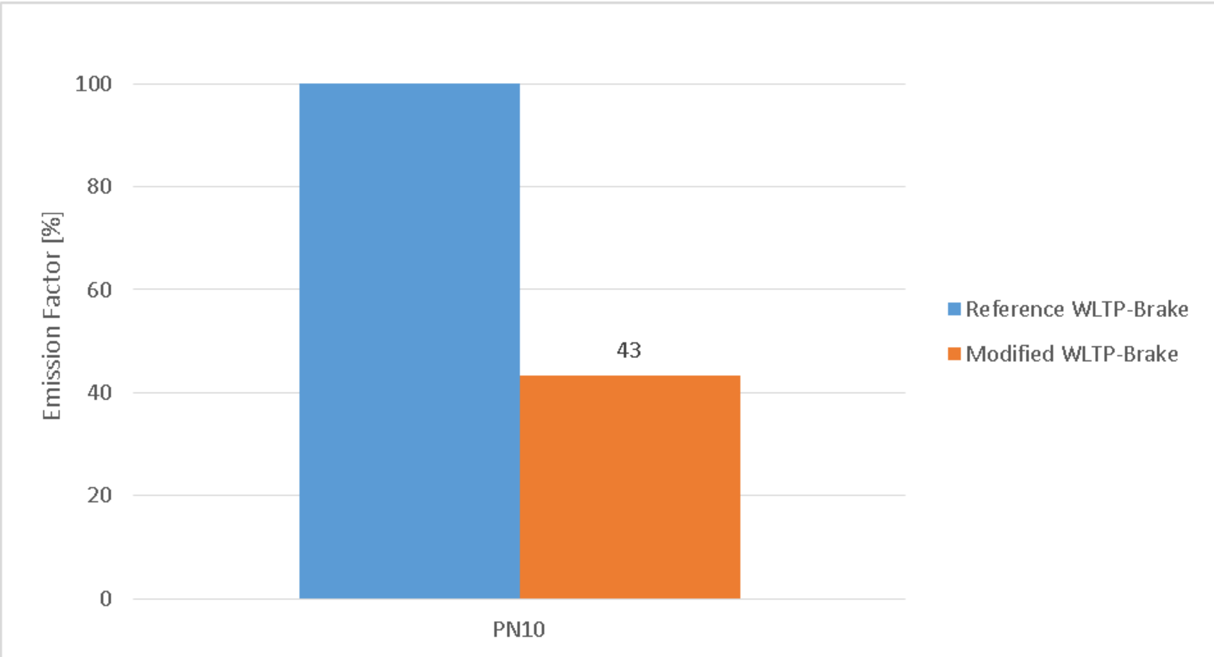
As can be noted from all the figures, the particle emission peak was always detected during the stop number 295, it is one of the most demanding stops of the entire WLTP-brake cycle.

3.4 Results of the emission tests

As mentioned in the previous section, the modifications of the testing cycle resulted in a decrease in the emitted particle masses and number. The relative PM_{10}, $PM_{2.5}$, PM_1 and PN_{10} emission factors are showed in Figure 3-14.



(a)



(b)

Figure 3-14: PM_{10}, $PM_{2.5}$, PM_1 (a) and PN_{10} (b) relative emission factors for the reference and the modified WLTP-Brake testing cycle

From the experimental activity carried out during T3.2 is clear that a significant reduction in the emissions coming from the wear of the braking components can be achieved with a more conservative driving behaviour. These results have been acquired with a dynamometric bench that is commonly used as one of the main testing apparatuses for brake components. These tests are aimed at simulating real driving cycles as the novel WLTP-brake one. All the modifications of the reference cycle simulated a higher attention of the driver to the traffic conditions and this led to:

- Lower initial brake speeds;
- Lower in-stop decelerations.

These changes resulted in a lower amount of kinetic energy and power dissipated by brakes that led to lower disc temperatures and thus emissions.

All the data collected in T3.2 have been shared with T3.5 which is aimed at creating a computational model for the simulation of the emission behaviour of a vehicle with different driving styles.

4. Tyre/Road emission methodology and measurements

4.1 Purpose of the exercise

In this subtask, the influence of driver's driving style on tyre mass-loss will be studied. Such information will be used in WP 5 as input for drivers' suggestions.

4.2 Test Vehicle Fleet

For the test campaign a pool of drivers was recruited amongst Rome (RM) Milan (MI) in Italy and Athens (AT) in Greece for a total of 81 vehicles. In Figure 4-1 the vehicle distribution per city is reported.

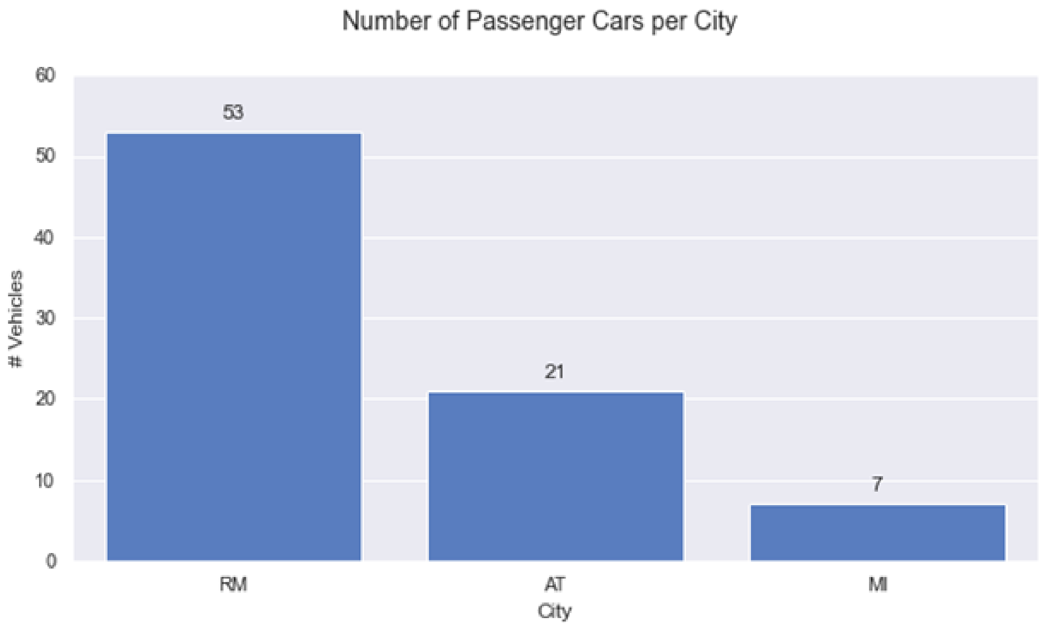


Figure 4-1: Vehicle distribution in each city

4.3 Test route

For this test, dedicated urban, extra-urban and Highway road were include based on real-life condition ref. on requested taxi services. As consequence of real-life services exploitation different driving environments (street, road, highway), and the traffic situation were quite spread depending on the day of the week or the hour of the day and route. Furthermore, the driver's individual driving style is an additional impacting parameter.

In the Figure 4-2 it is possible to see the average number of km done on different driving environments (Urban, Extra Urban, Highway)

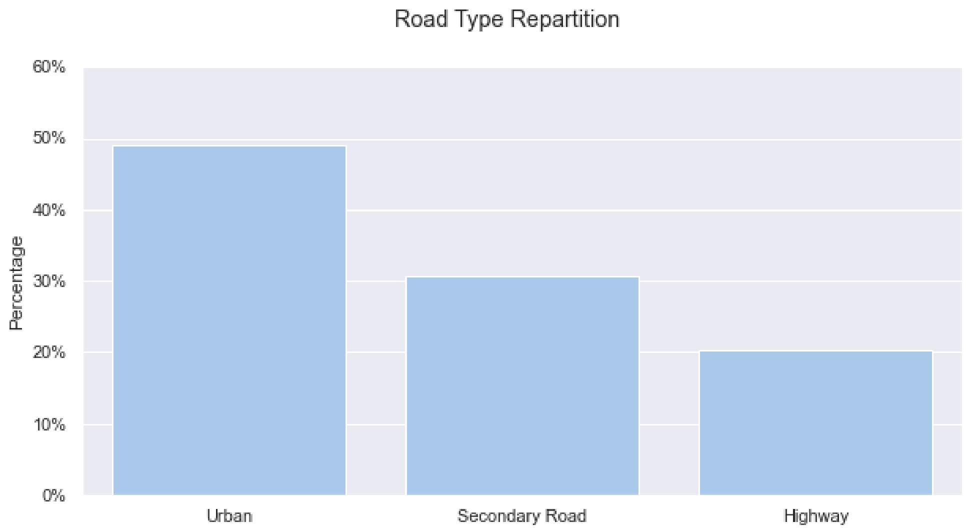


Figure 4-2: Average number of km travelled on different driving environments (urban street, secondary road, highway)

In Figure 4-3 the average number of km done per vehicle per month is reported dividing the information into 3 years (2019-2020-2021).

It is possible to observe the impact of Covid-19 on the usage of the vehicles. In 2019 and beginning of 2020 the average number of km per vehicle was about 4800 km (with expected more than 50000 km per year) while due to the Covid-19 the average was reduced to 2400 km.

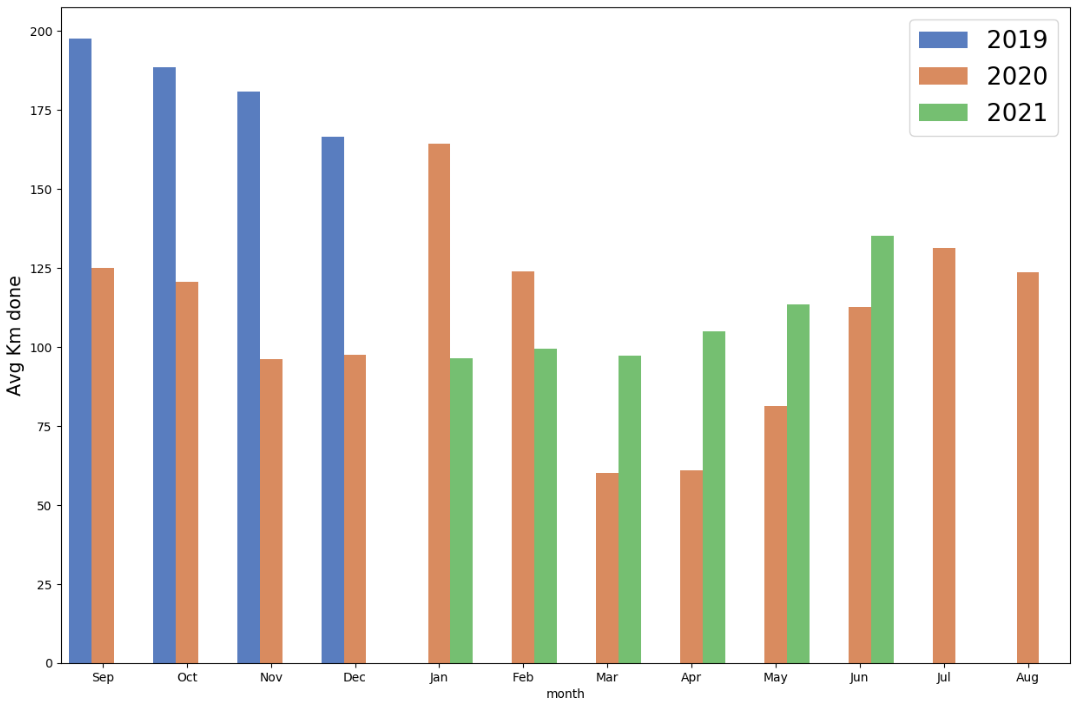


Figure 4-3: Average kilometres travelled by the vehicles engaged in the fleet test per months

Different colours show the distribution per years

In Figure 4-4 the speed profile (for speed larger than 0 km/h) of the vehicles involved in the test fleet is reported while in Figures 4-5 and 4-6 the longitudinal and the lateral accelerations of the vehicles are presented.

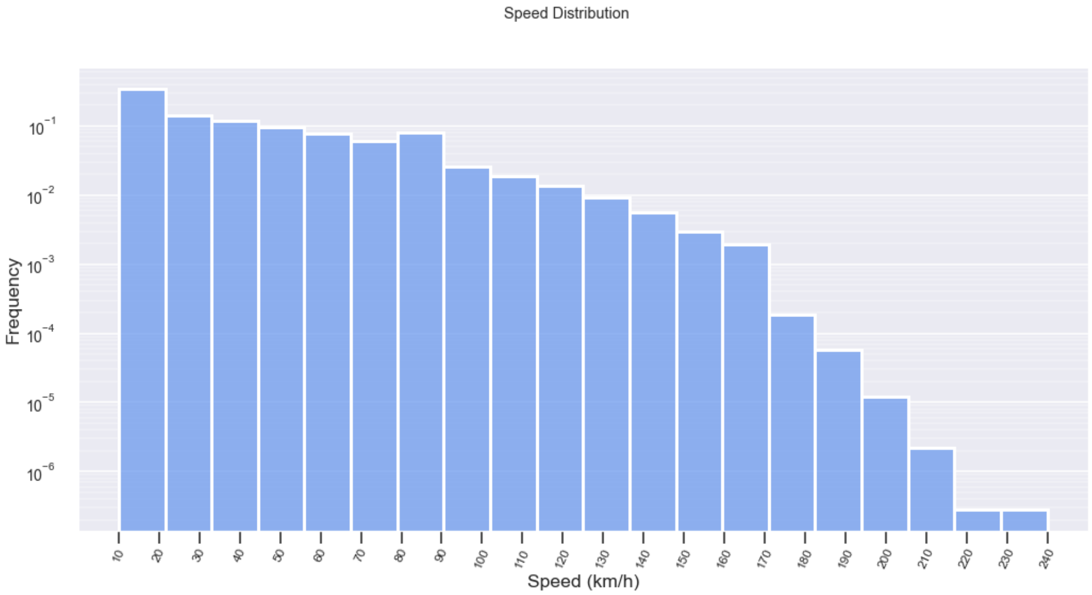


Figure 4-4: Speed distribution for all vehicles in the fleet

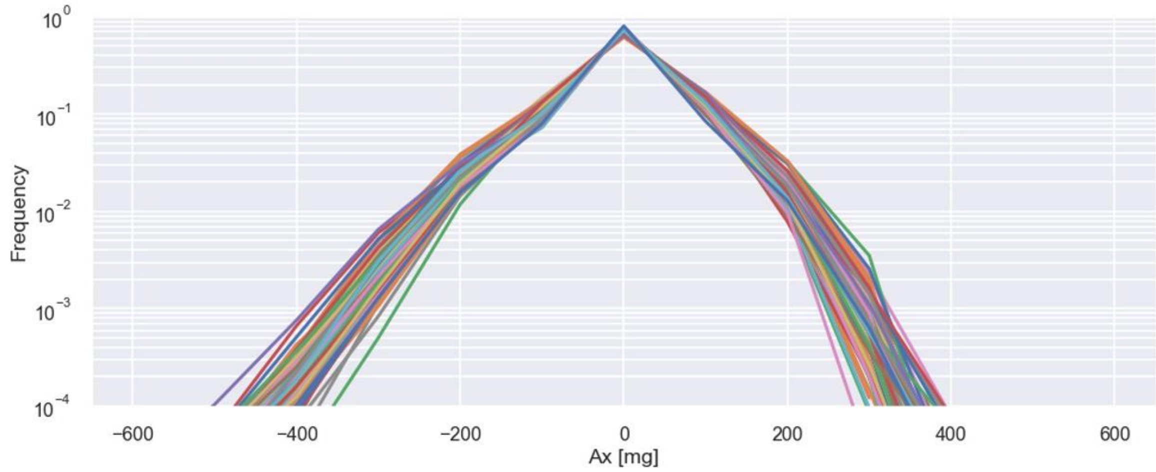


Figure 4-5: Longitudinal accelerations distributions for the vehicles in the fleet

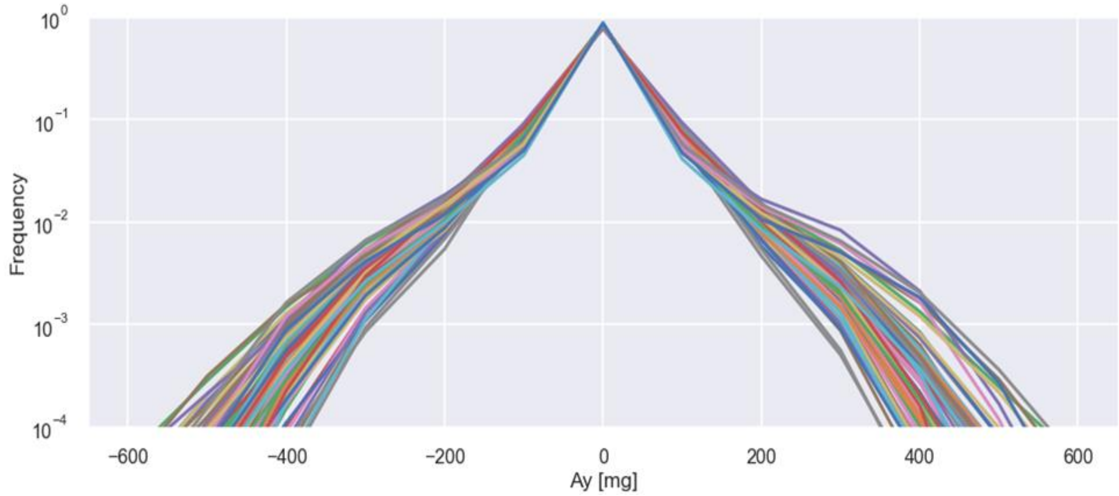


Figure 4-6: Lateral accelerations distributions for the vehicles in the fleet

4.4 Test vehicles and tyres sizes

To construct a robust campaign different vehicle, tyre size and tyre type were tested in different cities. In Table 4.1 the list of vehicles (with brand and type) is reported together with the population number while in Table 4.2 the list of tyre size with frequency.

Table 4.1: Table reporting the number of cars grouped into different vehicle brands

Vehicle Brand	Frequency
toyota prius plus	23
skoda octavia	22
toyota prius	9
mercedes b	9
ford c-max	6
toyota auris	5
volkswagen passat	4
skoda superb	3

Table 4.2: Number of Tyres grouped into tyre's size

Tire Size	Frequency
205/55R16	26
205/60R16	19
225/45R17	10
215/50R17	6
215/45R17	6
215/55R17	5
215/55R16	4
195/65R15	2
235/45R18	1
225/45R18	1
215/60R16	1

4.5 Test equipment

An OBD Dongle was used to acquire parameters in Table 4.3 during driving and collected in a cloud infrastructure.

Table 4.3: Parameters acquired and recorded by the data acquisition system

Influence domain	Controlled parameter	Physical parameter impacted
During driving	Longitudinal acceleration	Ax
	Lateral acceleration	Ay
	Average speed	< V >

While tyre data was collected periodically either with a manual device (depth gauge) or with an automatic drive-over ramp with laser scan technology obtaining wear tyre mass by calculation.

4.6 Validation and quality assurance

To ensure the data quality several checks are done before starting the test and also during the test (on vehicles and tyres). Checks could be divided into three groups:

4.6.1 Vehicle Preparation

a) Wheel Alignment:

Alignment setting prior starting test and check during periodical tyre/inspection/measurement must be done as per following OEM specification:

- Vehicle in Reference condition (load on vehicle axle during alignment measure)
- Reference angles (OEMs value +/- OEMs tolerance)

b) **Car Maintenance:** according to car manufacturer recommendations.

Daily inspection before starting driver have to check oil/water level, lights, the dashboard indicators (general mechanical conditions). If a mechanical problem is suspected, driver must stop immediately to drive and contact BS staff.

4.6.2 Tyre Preparation and Maintenance

a) Tyre mounting and balance;

- Clean tyre beads and rim bead seats
- Lubricate tyre bead with appropriate lubricant solution
- Mount tyre and rim (rim valve aligned to tyre DOT)
- Inflate at approx. 3 bars. After it adjust to car manufacturer ref. tyre pressure
- Balance tyre/rim assembly.

b) Tyre Check

On daily basis prior to start operations, driver must:

- Check tyre Inflation pressure
- Implement tyre visual inspection to detect possible tyre failure
- Activity must be stopped, if tyre failure is detected and immediately BS Ref. Staff contacted.
- Additional checks are done when tyre is monitored from Expert Technician (e.g. during tyre measurements)

4.6.3 Tyre Inspection / Wear Measurements

Inspection/measurement frequency

- First Tyre inspection: on new tyre (0 km-after tyre mounting and balance operation)
- Intermediate test inspection: every 3 months or 15.000 km
- Final Inspection: at test completion
- Tyre Visual Inspection and IP check implemented by Expert Technician

Tread Wear Measurement implemented by Expert Technician are taken with a precision of at least 0.2 mm.

4.7 Results

In Figure 4-7, the dissipated rubber volume is visualized based on the km travelled by all passenger cars in the fleet. The plot shows the consumption of rubber at different stage of the campaign and highlights the consumption respectively to per tyre's positions (FL for front left, RL for rear left).

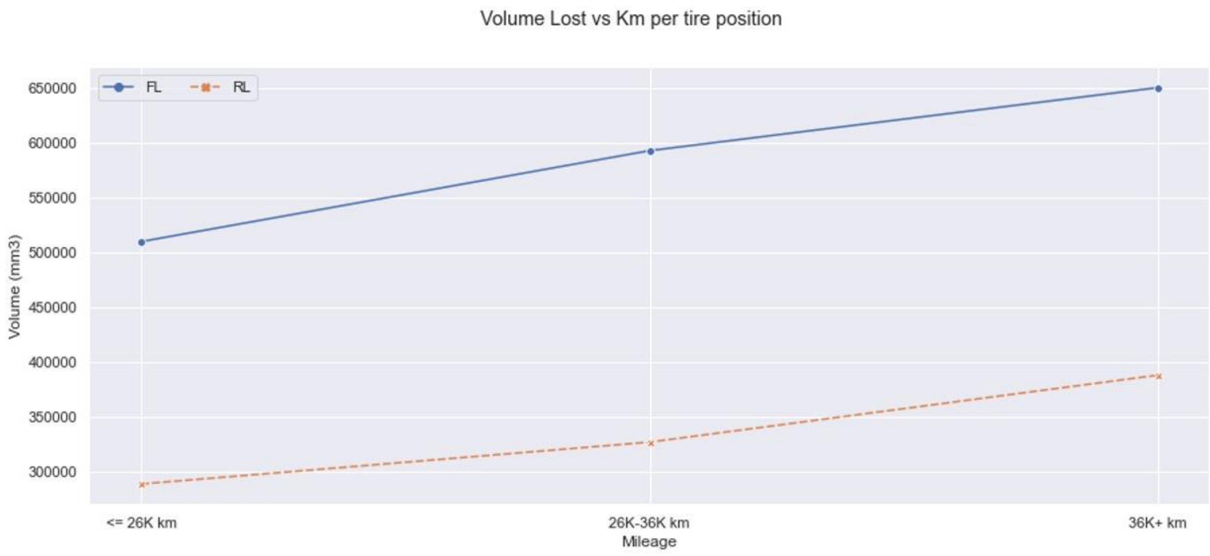


Figure 4-7: Behaviour of the rubber volume lost in terms of km done by the vehicles

4.8 Discussion

A clear difference was found in tyre wear between front and rear tyres, mainly due to the fact that all participating cars were front-wheel driven, which tends to put much more load on the front tyres, because they are responsible for both traction (longitudinal loads) and steering (lateral loads), whereas the rear wheels are just “free rolling” with much less forces applied. Apart from this quite obvious result, the effect of vehicle make/model and tyre size was also addressed, as well as different types of tyres (compounds). These were addressed in a more detailed analysis and discussion presented in Deliverable 3.2. The following is a synopsis of the main findings in that analysis.

The analysis revealed that tyre wear measurements vary substantially between tyre positions, vehicle types, tyre sizes as well as tyre types, and the collected data contained a considerable number of outliers. As the fleet size was quite limited, it was not clear whether this variability was acceptable and genuine, and caused by the different local road and environment conditions or was resulting from errors in the measurements. This also suggested that if the important factors in the driving behaviours, which result in outlier measurements, are not known, predictive models for simulating the tyre wear may not perform well.

Nonetheless, an attempt was made to quantify the link between tyre wear and driving behaviour by modelling. The work started by taking only a few major driving behaviour parameters and using a simple linear regression model for tyre wear prediction, and taking the average values for longitudinal accelerations, lateral accelerations and vehicle speeds as independent variables. However, this led to a poor correlation, indicating that the average values of longitudinal and lateral accelerations as well as vehicle speed cannot explain the variability of tyre wear measurements. Therefore, a more complex, non-linear modelling was implemented, with a more sophisticated non-linear fitting method based on machine learning, including classification, regression, and ranking tasks. As the result of this exercise, an adequate level of understanding about the relative importance of featured parameters affecting tyre wear rates was achieved.

5. Maintenance and tampering

5.1 Purpose of the exercise

These experiments were aimed at judging the influence of maintenance on exhaust emissions.

5.2 Test cars

In these tests both petrol and diesel fuelled cars were used. All cars were sourced from VTT's personnel, and they were passenger vehicles in normal private use. For the purpose of detecting maximum effect, cars with high odometer reading and more driving after last scheduled maintenance were preferred. Table 5.1 lists some main characteristics of the test cars fuelled with petrol, and Table 5.2 those fuelled with diesel fuel.

Table 5.1: Petrol-fuelled test cars used to study the influence of maintenance

Car	SP1	SP2	SP3	SP4	SP5	SP6
Make	Alfa Romeo	Hyudai	Kia	Seat	Seat	VW
Model	159 SW	i20	Venga	Ibiza ST	Leon	Polo
MY	2006	2012	2012	2013	2011	2009
Odometer (km)	197 000	170 000	96 000	140 000	138 000	145 000
Engine (dm^3)	1.9 GDI	1.3	1.4	1.2	1.4	1.4
Power (kW)	118	57	66	77	92	59
EAT	TWC	TWC	TWC	TWC	TWC	TWC
Euro TA	2003/76B (Euro 4)	692/2008F (Euro 5)	692/2008F (Euro 5)	566/2011F (Euro 5)	692/2008A (Euro 5)	2006/96B (Euro 4)

Table 5.2: Diesel-fuelled test cars used to study the influence of maintenance

Car	SD1	SD2	SD3	SD4	SD5
Make	BMW	VW	Skoda	Audi	Ford
Model	316d	Passat	Octavia	A4 Avant	Focus
MY	2011	2013	2012	2011	2011
Odometer (km)	273 000	291 000	197 000	330 000	272 000
Engine (dm^3)	2.0	1.6	1.6	2.0	1.6
Power (kW)	85	77	77	100	80
EAT	EGR, DOC, DPF	EGR, DOC, DPF	EGR, DOC, DPF	EGR, DOC, DPF	EGR, DOC, DPF
Euro TA	692/2008A (Euro 5)	566/2011F (Euro 5)	566/2011F (Euro 5)	715/2007 - 692/2008A (Euro 5)	692/2008A (Euro 5)

5.3 Contents of the tests

Cars were first tested in "as delivered" status, and then a maintenance was performed according to the manufacturer's recommendation for that odometer reading or other reference. Usually, this encompassed change of engine oil and filter, change of air induction filter, as well as a number of checks on brakes etc. to ensure that they are not binding. In addition, spark plugs were changed in all cases of petrol-fuelled cars, even if the schedule did not suggest their change. This was in order to maximise the influence of the operation.

All old parts were retained for visual inspection and for the records, all were also photographed.

The cold-start NEDC cycle was used as the first test, followed by a warm-start ARTEMIS Urban cycle. This cycle is a “real-world” cycle, developed in the European ARTEMIS project in early 2000. It is quite widely used for testing purposes, when a “non-standard” cycle is needed. Then, the basic scheme for all cars consisted of one NEDC cold followed by one ARTEMIS warm (day 1), and subsequently, WLTC cold followed by one ARTEMIS warm (day 2). With some cars an additional NEDC test was performed before the first, preconditioned test to establish some basic performance level of the car, but this test was not “official” as there was no formal preconditioning, and sometimes the soak time before the test was not according to the requirements

5.4 Test equipment

For the in-laboratory chassis dynamometer measurements, normal CVS-based exhaust dilution and (bag) sampling was employed. The system used was manufactured by AVL, and consisted of i60-series of equipment, i.e. i60 CVS, i60 Emissions analyser bench and i60 PSS particulate matter sampling system. In addition, a separate apparatus was used for particulate number (PN) determination. Table 5.3 lists some details of the equipment and their main characteristics. The system as a whole conforms with regulatory requirements for light-duty vehicle exhaust emissions measurements. Furthermore, VTT is accredited to perform such measurements for legislative uses, although the measurements in this particular exercise were not following rigorously the accredited protocols.

Table 5.3: Exhaust emissions measurement system for in-laboratory chassis dynamometer tests

Device	Specification	
Chassis dynamometer	FroudeConsine (UK)	1 m roller, max power absorption 100 kW, inertia 450 – 2750 kg
Exhaust gas dilution & bag sampling system	AVL CVS i60 (CFV)	flow rate 3 – 18 m^3/min, 4+4 bags
Exhaust gas analyser	AVL AMA i60, with the following modules:	
	CO (NDIR)	0..50 ppm / 0..5000 ppm
	CO_2 (NDIR) low	0..0,1 % / 0..6 %
	CO_2 (NDIR) high	0..0,5 % / 0..20 %
	NO, NO_2 (CLD)	0..3 ppm / 0..1000 ppm
	THC (FID)	0..3 ppm / 0...1000 ppm
	CH_4 (FID)	0..9 ppm / 0..1000 ppm
Particulate number (PN)	Airmodus A23,	Butanol Condensation Particle Counter (bCPC)
Particulate mass (PM)	AVL i60 PSS, sampler	4 channels/filter holders
Microbalance	Sartorius SE2-F	0 ... 2100 mg, 0,1 µg increment

Figure 5-1 depicts a schematic outline of the complete test set-up, and Figures 5-2 and 5-3 depict the test cell and some individual main components of the equipment.

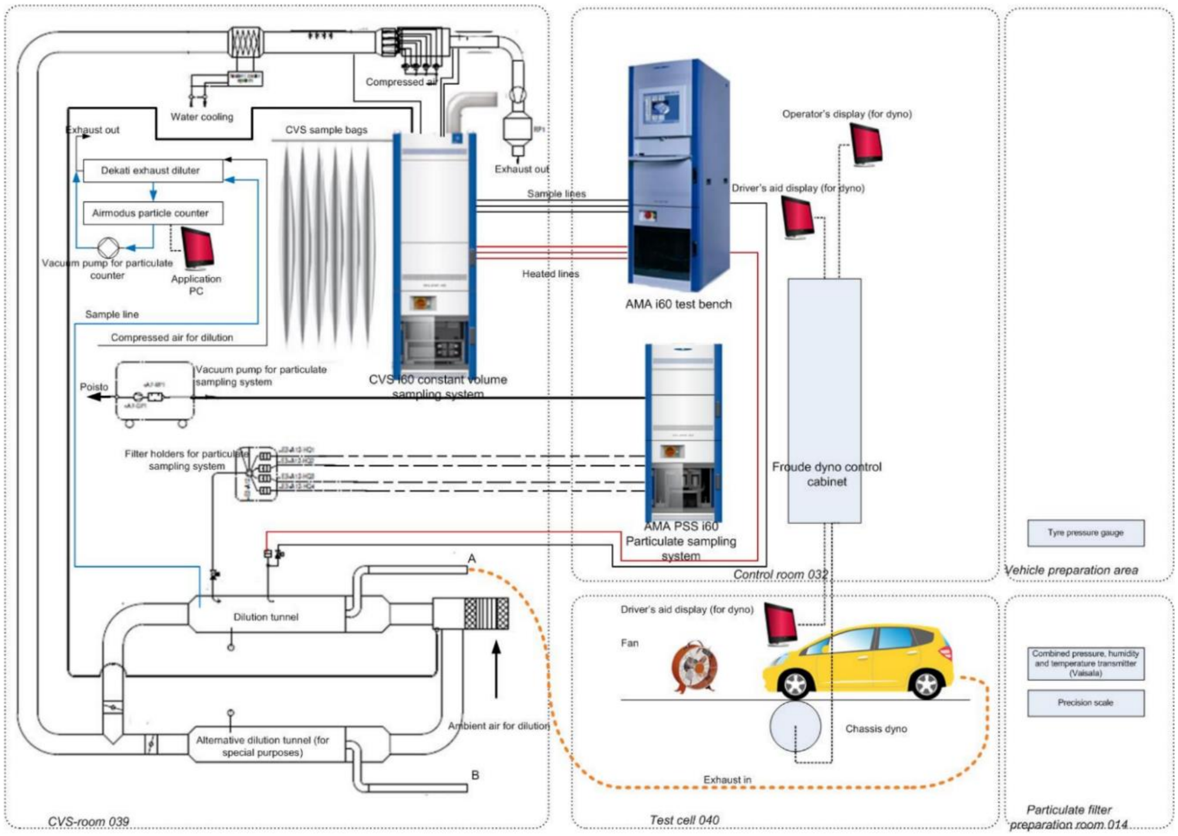


Figure 5-1: Schematic layout of VTT's light-duty vehicles chassis dynamometer measurement system

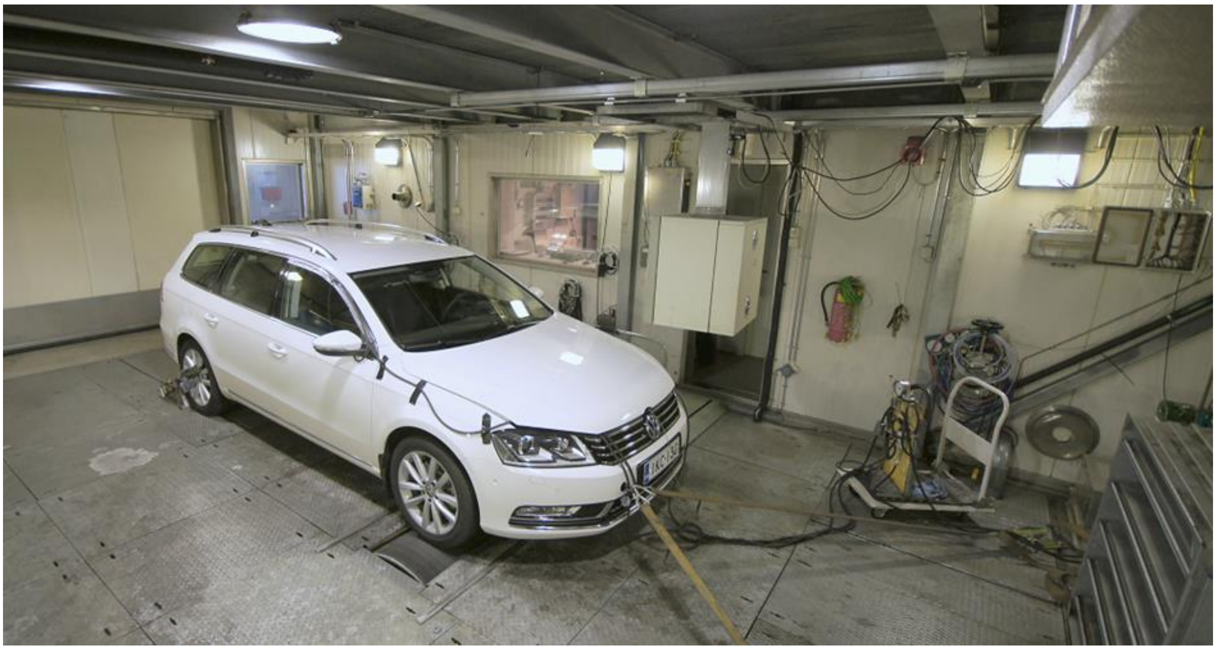


Figure 5-2: Emissions and fuel consumption test facility with a single-roller 2WD dynamometer

Figure 5-3: AVL i60 Emissions Analyser + i60 PSS (left photo) and AVLi60 CVS + sampling bags

5.5 Validation and quality assurance

The validity and quality of these test results was assured by the quality system that VTT carries for light-duty vehicle exhaust emissions tests that are also accredited. It is mainly built around the widely used and well-proven scheme of using known standard calibration gases and frequently running calibration checks. With annual maintenance and linearity checks, the system is delivering consistent and valid results.

Furthermore, ambient conditions are measured and recorded, and used to normalise the results. In addition, the crew that were running the tests are experienced experts that have made these kind of tests for several years.

5.6 Results for petrol-fuelled cars

The results of this set of measurement are presented in the following graphs. At first, Figures 5-4 and 5-5 portray the results of the initial, pre-service measurement(s) against the type approval results, and the corresponding EU-limit values. Type approval values are the figures manifested in the Certificate of Conformity (CoC) of that particular, car and included in their official motor vehicle registration data. Due to the scaling, CO is presented in a separate box, and the other substances in another.

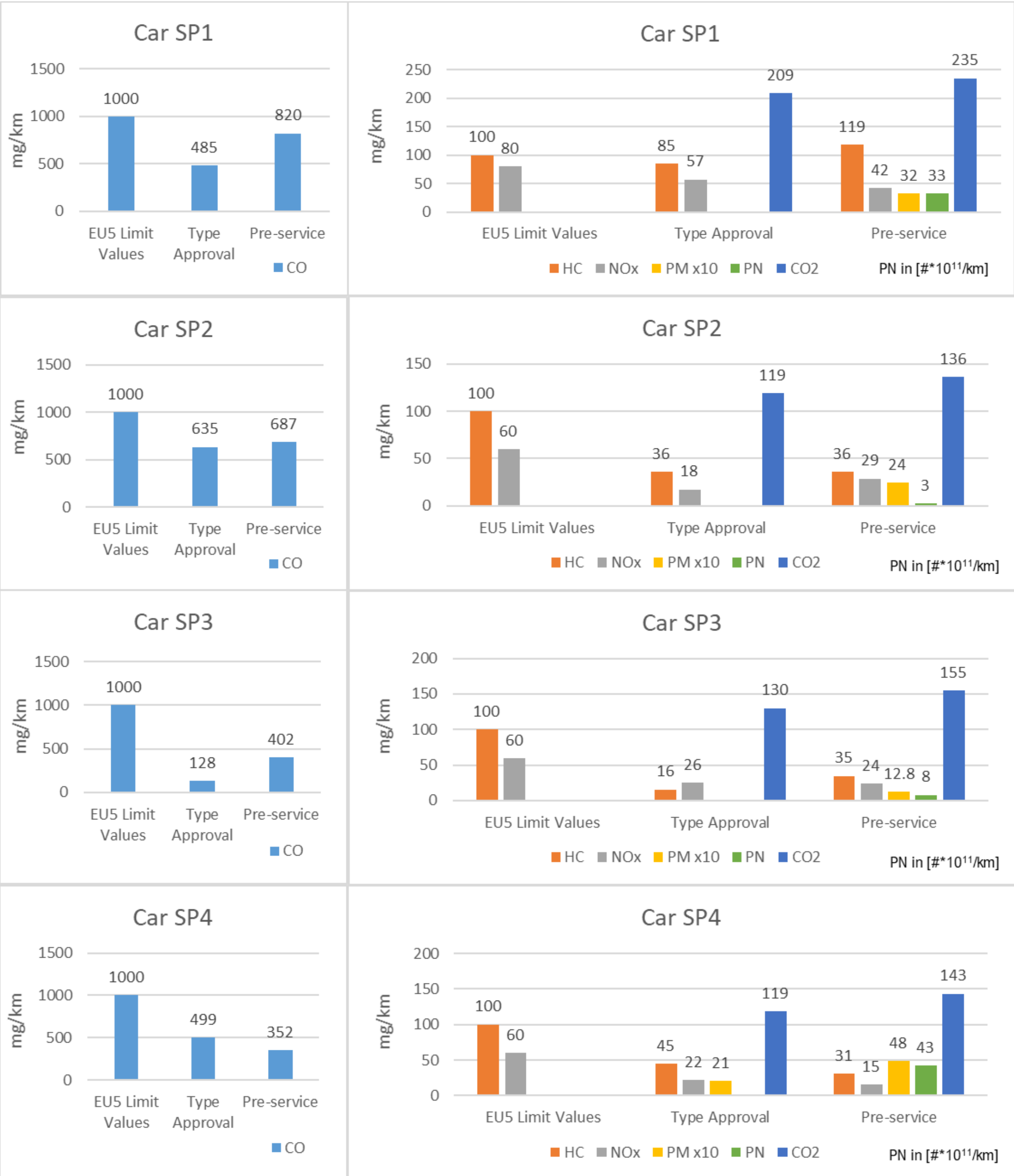


Figure 5-4: EU-limits, type approval figures and measured pre-service emissions in NEDC cycle, Cars SP1, SP2, SP3, and SP4

Figure 5-5: EU-limit values, type approval figures and measured pre-service emissions in NEDC cycle, Cars SP5 and SP6

As the graphs show, apart from car SP5, which showed an atypically high CO result, all were within their Euro 5 limit value bracket, and one (SP2) very close or one (SP4) even below the type approval value of that specific car. Regarding total HC, only car SP5 showed very high emissions in the pre-service measurements, while the other were below the EU limit value, and close to their type approval figures. What comes to NOx, only cars SP2 and SP6 presented results that were higher than their type approval figures, but even those were clearly below the EU limit value.

Quite as expected, none of the cars could match their type approval figure for CO_2-emissions, as it was quite typical for this era that the type approval figure for CO_2 was “engineered” to be very low, and replicating that result was very difficult in subsequent tests in real-life, and especially cars that were driven from 100 000 to close of 200 000 km. All and all, the test cars seemed to be in fairly good state even before the service, apart from those few exceptions mentioned.

Then the results of the post-service measurements are presented in Figures 5-7 and 5-8. As we were here mainly interested in the change in emissions output, the results are all presented as relative to the level of emissions recorded in the pre-service tests. Thus, it is very easy to see the direction of the change, as well as the potency. Tests with cold-start NEDC and warm start Artemis Urban are shown separately.

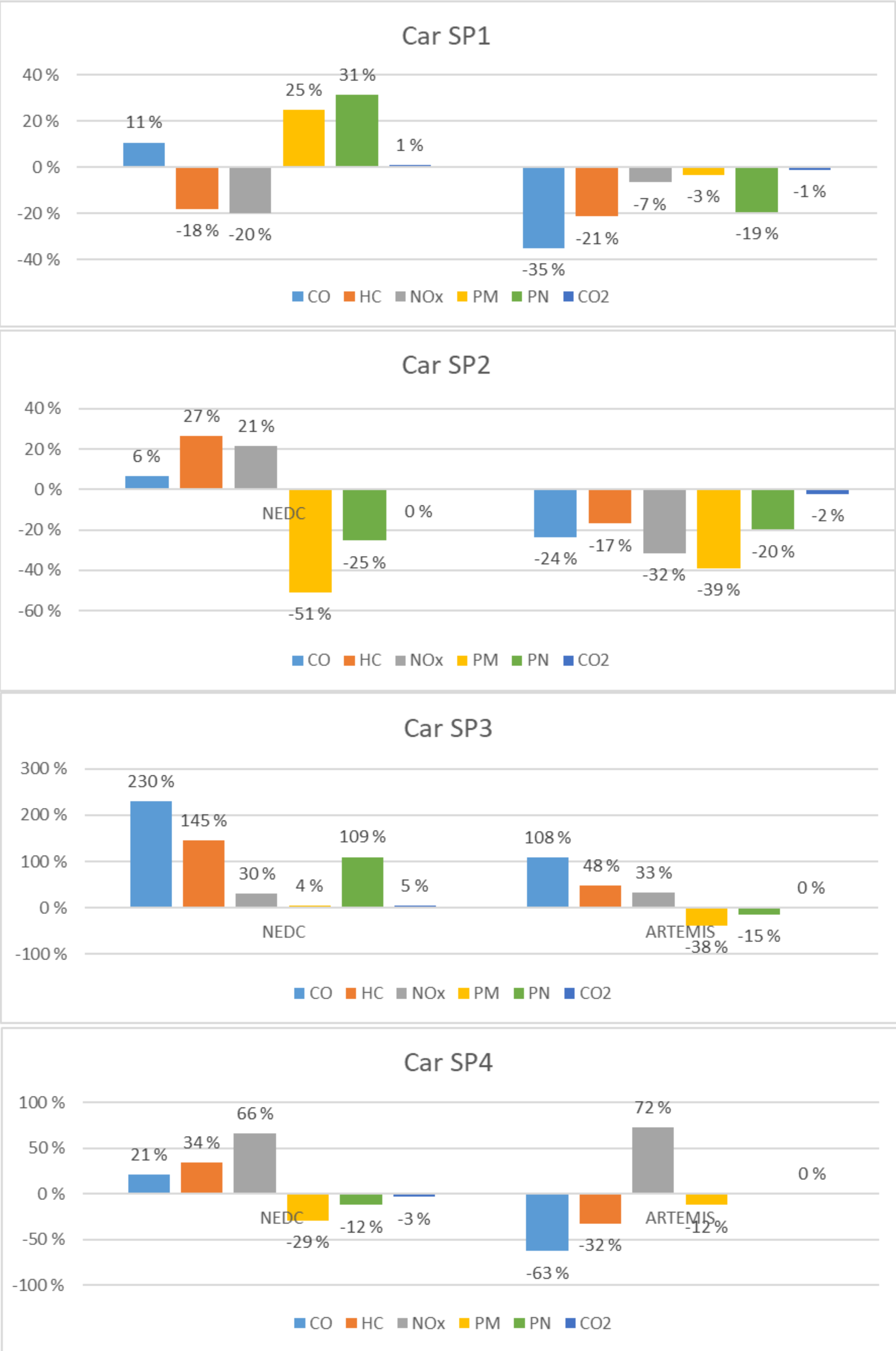


Figure 5-6: Relative change in exhaust emissions with NEDC (left) or ARTEMIS Urban (right) test cycles; Cars SP1 to SP4

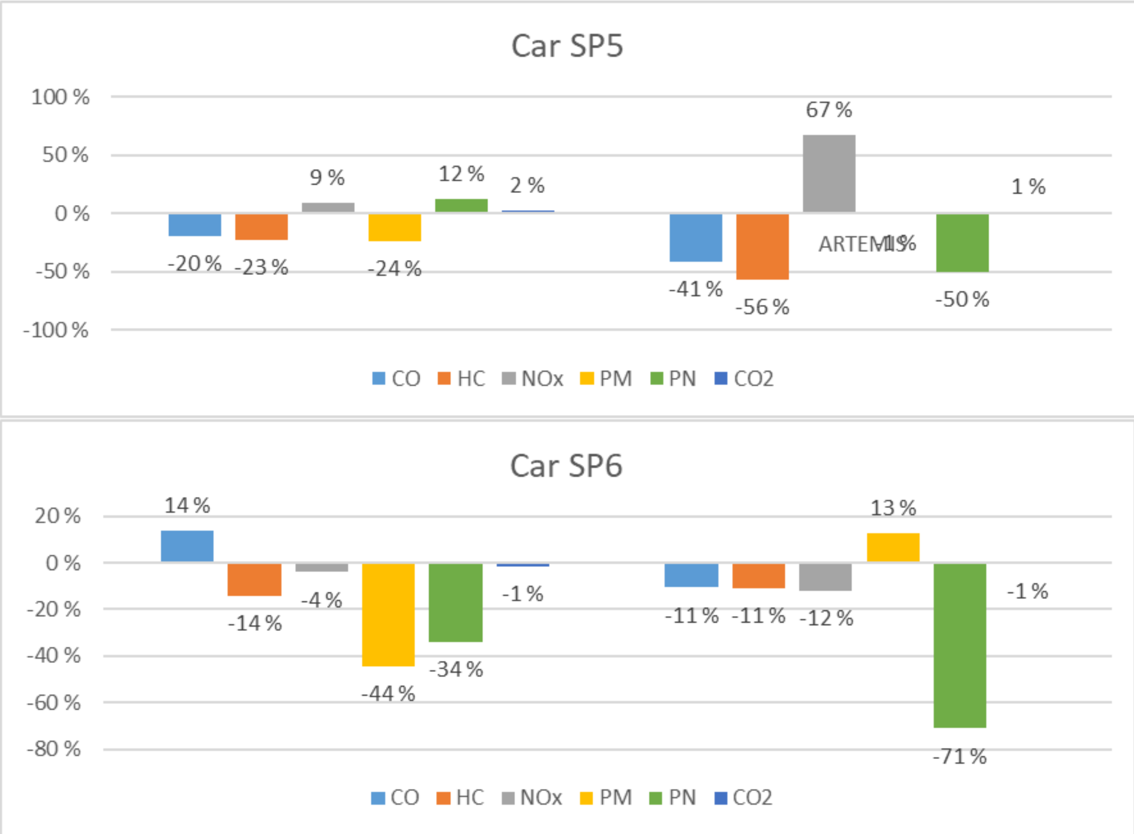


Figure 5-7: Relative change in exhaust emissions with NEDC (left) or ARTEMIS Urban (right) test cycles; Cars SP5 and SP6

According to the results portrayed in these graphs, the overall conclusion was that the service did not attribute only positively, with less emissions after the service than before. Instead, the changes were different from car to car, also regarding the species and test type. If we count the observed cases, we have for each car six results with NEDC cycle and another six for the ARTEMIS test, totalling 72[1] individual cases for the six tested cars. With the cases based on NEDC tests, 15 (out of 36) showed lower emissions after the service, but in total 20 cases presented higher emissions, while one case regarding CO_2 was a tie, with no apparent change. On the other hand, in the warm start ARTEMIS test, 26 cases (out of 35[1]) exhibited lowering of the emissions, while seven showed higher emissions in post-tests. Two ties were also recorded, again on CO_2, which was the least-effected species, overall.

If we count all cases regarding CO emissions, we can see that in all but one post-service cold-start NEDC tests, CO increased from a negligible (6%) to a large (230%) amount, while one car (SP5, with the highest absolute level of CO in pre-service tests) showed a 20% decrease. Furthermore, in all but one case (car SP3) CO decreased in warm-start ARTEMIS Urban tests, and the decrease was between 11% and 41%, while the increase for car SP3 was a considerable 108%.

What comes to total hydrocarbons (HC), in all but two cases (cars SP5 and SP6) the emissions increased in NEDC tests from a minimal level (+6%) to a quite significant level (+145%), while the two decreases were quite low, -14% to -23%. In the ARTEMIS Urban tests, five out of six cars showed a

[1] Actual figure is 71, as for Car SP4, the PN result for pre-service test in ARTEMIS cycle is missing, voiding the comparison to the after-service results.

decrease (between -11% and -56%), but one car (SP3) reacted with increased emissions by an almost 50% increase.

If we consider NOx emissions, the results form NEDC tests showed low to medium increase (+9% to +66%), while two cars (SP1 and SP6) recorded a very slight decrease of -4%. In ARTEMIS Urban tests, the field was even stronger divided, as three cars (SP3, SP4, SP5) presented a medium to strong increase (+33% to +105%), while the other three yielded to a slight to medium decrease (-7% to -32%).

Overall, the changes were mostly positive for PM emissions, regarding both NEDC and ARTEMIS Urban test results. There were only two cases, where PM was higher in post-service tests. Those were car SP3 in NEDC (+4%), and car SP6 in ARTEMIS Urban (+13%). While the absolute level of PM emissions were also the lowest with these two, the measurement accuracy and repeatability/reproducibility issues come also to play, as both pre- and post-service tests include some level of inaccuracy, and when the absolute changes are small, these inaccuracies can confuse the outcome.

With only a few exceptions, PN emissions followed PM emissions, which is quite logical. However, there were a few cases where the opposite was found, like for car SP6, where in ARTEMIS test PM increased somewhat (+13%), but PN decreased significantly (-71%). Vice versa, with car SP5 in NEDC test the PM emissions decreased by 24%, but PN rose by 12%.

To address the effect of measurement inaccuracy, and to test how robust the observed changes in emissions levels were, the results of both pre- and post-service tests have been entertained with suitable levels of inaccuracy, which was ±2.5% for CO, ±7.5% for HC, NOx, PM and PM, as well as ±1% for CO_2. These values were stemming from the average levels between the two pre- and post-service tests run in this exercise. With these inaccuracy factors both 'low' and 'high' results were calculated, based on the nominal result, and this was done both for pre- and post-service test results. With these numbers, two additional comparison were made, comparing the 'high' pre-service result with the 'low' post-service figure that should give the maximum attained change, as well as the other way round, comparing the 'low' pre-service result with the 'high' post-service figure that should signify the minimum level of change. In the middle there is the case already considered, where the nominal values were compared.

The results of this kind of sensitivity analysis are presented in Figure 5-8 that portrays the aforementioned comparisons for each of the six tested petrol-fuelled cars. It gives a quick way of judging the net change, because is both minimum (MIN) and maximum (MAX) bars point to the same direction, the change is robust, but if either of the bars point to the opposite direction compared to the other bar, the case is weak, because then the measurement inaccuracies are on the same level as the observed change, and thus can "dilute" the effective change. As we see from the separate graphs for both NEDC and ARTEMIS Urban cycles, the outcome is also strongly dependent on the cycle used.

Based on the results presented in Fig 5.8, a simple table (Table 5.4) has also been created. It shows the change in emissions in a three-grade scale, either increase (+1, +2, +3) or decrease (-1, -2, -3), and with no definite change, the score is 0. As oxides of nitrogen (NOx) and particulates (PM and PN) can be considered to be more significant than the other species in terms of their negative impact on air quality, their individual scores has been multiplied by two, when counting the combined scores.

Combined scores were counted separately for each car, test type and species, as well as totals.

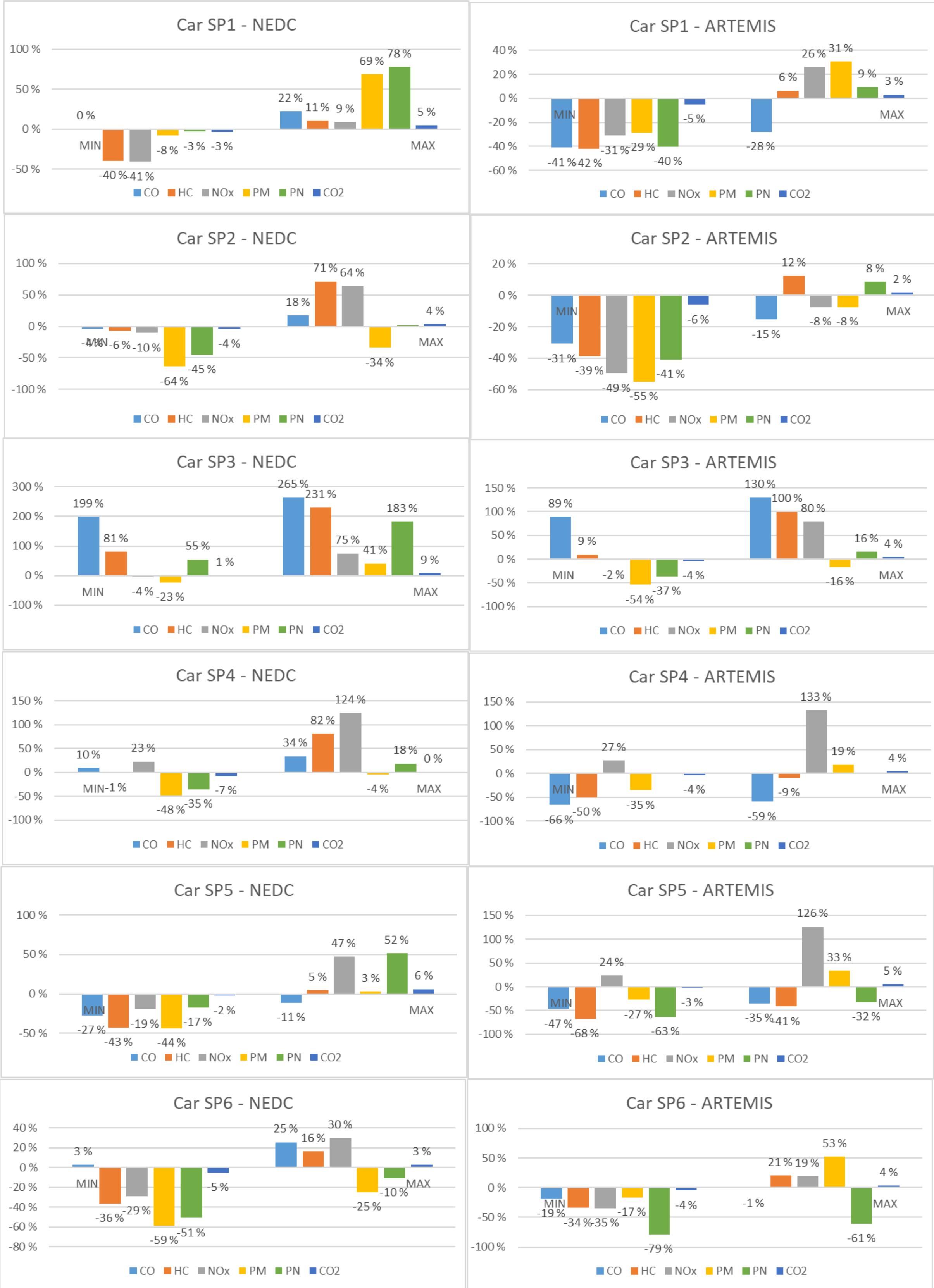


Figure 5-8: Sensitivity of the relative change in exhaust emissions with NEDC or ARTEMIS Urban test cycles; Cars SP1 to SP6

Table 5.4: Changes in emissions in NEDC and ARTEMIS tests, petrol-fuelled cars

	NEDC						ARTEMIS						COMBINED		
	CO	HC	NOx	PM	PN	CO2	CO	HC	NOx	PM	PN	CO2	NEDC	ARTEMIS	SUM
Car SP1													2	-9	-7
Car SP2													0	-13	-13
Car SP3													+17	0	+17
Car SP4													5	+2	+7
Car SP5													-4	-+3	-7
Car SP6													-9	-+3	-12
NET SUM	+6	+6	+7	-12	4	+1	-7	-3	+4	-6	-6	0	**11**	**-26**	**-15**

strong	medium	slight	increase	strong	medium	slight	decrease	In case of NOx, PM and PN,
+3	+2	+1	increase	-3	-2	-1	decrease	the score is multplied by 2
0	indiffrent, no definite change			0	indiffrent, no definite change			

Based on the combined scores presented in Table 5.4, we can conclude that the basic service and maintenance operations that were performed had the most positive effect (highest negative score) on car SP2, while SP6 was the second in a row, and cars SP1 and SP5 contributed also to the lowering of emissions. On the other hand, cars SP4 and especially SP3 presented post-service results that attributed increase in emissions, an unwanted result. Overall, the decreases in emissions seemed to be stronger in ARTEMIS Urban test compared to NEDC tests, which actually got a slightly positive score indicating an increase in emissions. However, as ARTEMIS cycle represents more “real driving”, for the impact point of view, it is more important that more favourable emissions performance was presented in test using this driving cycle.

5.7 Results for diesel-fuelled cars

A second batch of vehicles consisted of five cars with diesel engines. Details of these cars are in Table 5.2. Because diesel cars are usually driven more than petrol-fuelled, the odometer reading of these vehicles were also higher than in petrol-fuelled one’s, and the lowest reading for diesels was equal to the highest value for petrol cars, and the highest reading exceeded 300 000 km, whereas the remaining three were somewhat below the 300 000 mark.

Like for the petrol-fuelled cars, the results for the diesel-fuelled ones are depicted in two type of graphs. First in Figure 5-9 the test results of the pre-service NEDC cycle test are presented alongside the EU limit values and type approval (TA) test results for that specific car. Then, the relative change in emissions after the service are presented in Figure 5-10, and finally in Figure 5-11, results of the sensitivity analysis (similar with the one for petrol-fuelled cars) are depicted.

Starting from Figure 5-9, it can be seen that two of the tested diesel cars presented CO-emissions that were higher than their official Type Approval levels while three had emissions lower than the TA level. All except one case (SD2) the HC emissions were higher than the corresponding TA level, but all were still below the EU5 limit value. None of the tested cars could match their type approval NOx level, and only one (SD4) had emissions below the legal limit value. This was not unexpected, as these cars originated from the era that real-world NOx emissions were somewhat debateable due to the technology being underrated for the task. Regarding particulate mass (PM), all but one car (SD5) had normal levels well below the EU5 limit value, and about the same level as their TA results. However, car SD5 had apparently a broken DPF, as it presented an order of magnitude higher PM than the others, and especially very high particulate number (PN) result that exceeded EU5 limit value by a factor of almost 20, and this PN level was more than 100 times the level found in other tested cars.

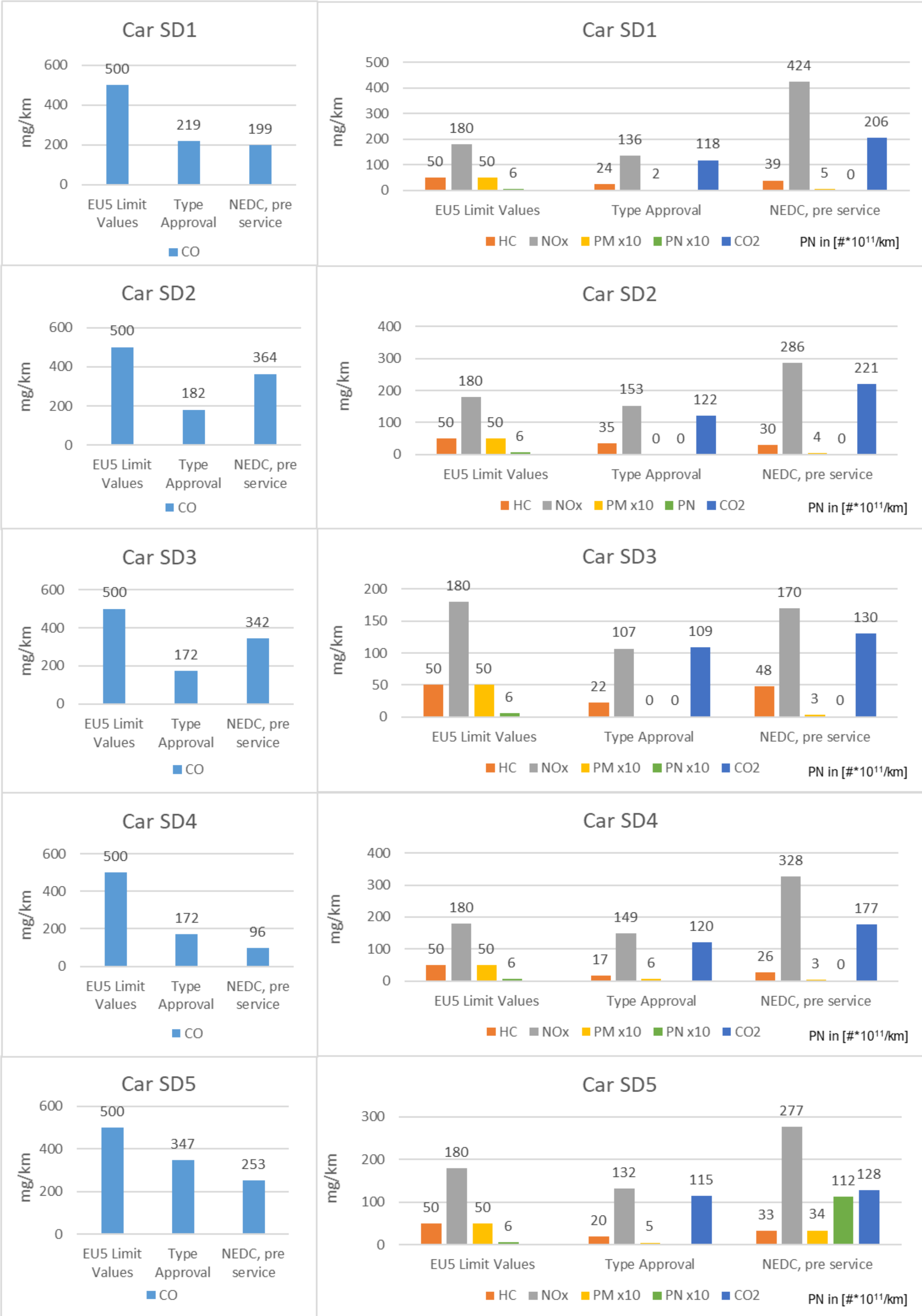


Figure 5-9: EU-limit values, type approval figures and measured pre-service emissions in NEDC cycle, diesel cars

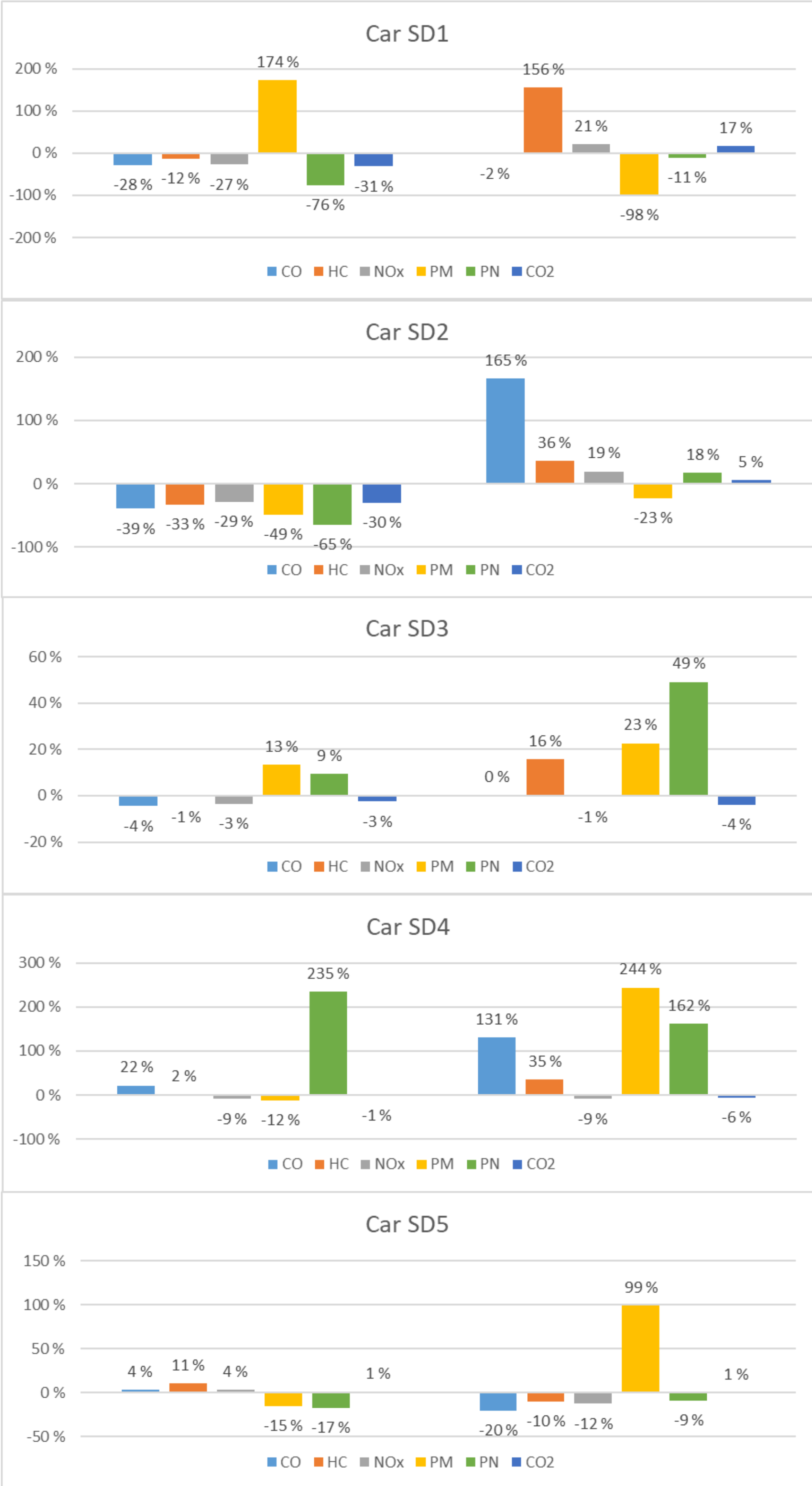


Figure 5-10: Relative change in exhaust emissions with NEDC (left stack) or ARTEMIS Urban (right stack) test cycles, diesel cars

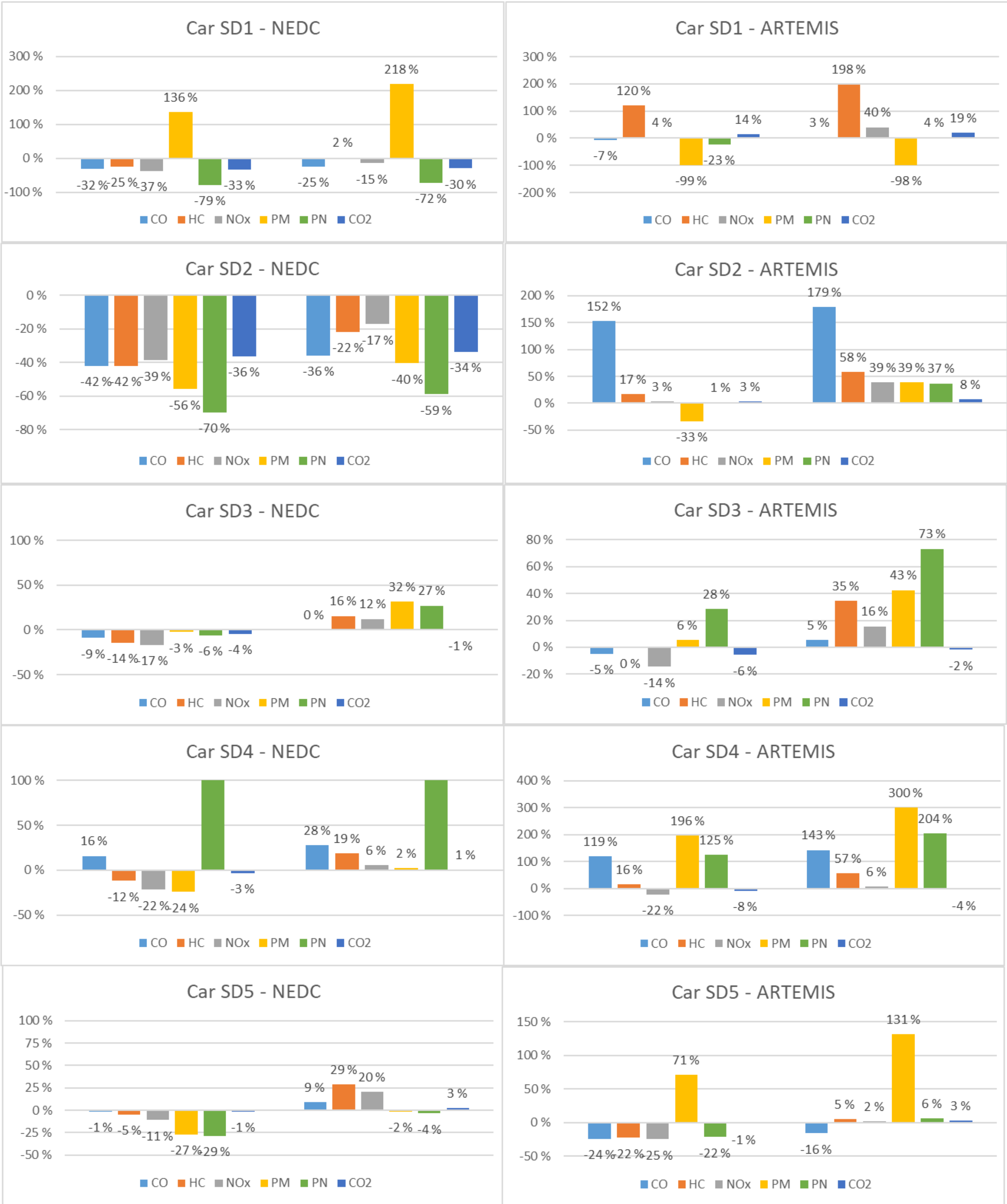


Figure 5-11: Sensitivity of the relative change in exhaust emissions with NEDC or ARTEMIS Urban test cycles; diesel cars

Considering the relative changes due to the service and maintenance performed, the responses varied from one car to another considerably. Also, the test cycle had an effect, because the responses were different in most cases, not only by the magnitude, but also by the direction of the change. As with the petrol-fuelled cars, each car had 6 + 6 cases (six emission types and two test cycles), and in total, this counts 60, of which 32 presented a change in decreasing emissions, but almost as many (27) pointed to the opposite direction, while one case was a tie, no apparent change.

Between the cycles the cases divided so that with the NEDC cycle, in 20 out of 30 cases the emissions decreased due to the service, while with ARTEMIS cycle in only 12 cases the emissions decreased, and in 17 emissions increased. However, as many of the changes were rather small, a sensitivity analysis was necessary to test the “robustness” of the change.

Figure 5-11 summarises the results of the sensitivity analysis, and shows that for Car SD1, most of the changes were definite, and only two were falling within the margin of error in the test procedure. Furthermore, it was notable that a considerable increase in PM emissions were encountered in NEDC, whereas almost as large decrease was recorded in the ARTEMIS cycle. On the other hand, fuel consumption decreased in NEDC, but increased in ARTEMIS, but with a lesser extent. Furthermore, Car SD2 was even more clear case, because in NEDC tests, all the emissions were definitely decreased, while with ARTEMIS, all others but PM were increased, but not so strongly, and with PM, the case was ambiguous.

The results for car SD3 show, that with NEDC cycle, there was no definite change due to the service in emissions levels. Only CO_2 showed a very slight decrease. This small decrease was also observed with ARTEMIS cycle, but HC, PM and PN clearly increased, while CO and NOx were open cases, if the margin of error was applied to the results. Car SD4 presented even more disappointing results, as there was only a slight definite decrease observed in CO_2 with ARTMEIS cycle, while CO and PN were definitely increased in both cycles, as well as HC and PN increased in ARTEMIS cycle test. For the last remaining car SD5, decrease in particulates (both PM and PM) were eminent in NEDC test, but with ARTEMIS the PM increased significantly while the change in PN remained unsettled. In addition, a slight decrease in CO emissions in ARTEMIS was documented, while HC, NOx and CO_2 remained on an uncertain level.

As a summary of the results for diesel cars, Table 5.5 concludes, how the service affected to the emissions in both NEDC and ARTEMIS tests.

Table 5.5: Changes in emissions in NEDC and ARTEMIS tests, diesel-fuelled cars

	NEDC						ARTEMIS						COMBINED		
	CO	HC	NOx	PM	PN	CO2	CO	HC	NOx	PM	PN	CO2	NEDC	ARTEMIS	SUM
Car SD1													-11	+3	-8
Car SD2													-25	+12	-13
Car SD3													-1	+9	+8
Car SD4													+5	+16	+21
Car SD5													-4	0	-4
NET SUM	-5	-3	-4	-3	-4	-6	+5	+8	+3	+4	+6	+1	**-36**	+40	+4

strong	medium	slight	increase
+3	+2	+1	increase
0	indiffrent, no definite change		

strong	medium	slight	decrease
-3	-2	-1	decrease
0	indiffrent, no definite change		

In case of NOx, PM and PN, the score is multplied by 2

Based on the combined scores presented in Table 5.5, we can conclude that the basic service and maintenance operations that were performed had the most positive effect (highest negative score) on car SD2, while car SD1 was the second in a row, and car SD5 also contributed positively. However, car SD3 and especially car SD4 recorded predominantly higher emissions levels after the service. As already discussed before, using the NEDC cycle produced more positive results (decreases in emissions) while the ARTEMIS cycle had the opposite effect. This can be seen in the net sum row, which is all green for NEDC, and results to a combined score of -36, while the corresponding score for ARTEMIS cycle was +40, leading to a total score of +4, which can be interpreted that the service operations had hardly any net effect on the emissions, and much less than with petrol-fuelled cars that scored in total -15, a much more favourable net result.

5.8 Results for diesel particulate filter renewal

Based on the pre- and post-service tests, the PM and especially PN levels were abnormally high in car SD5, suggesting a fault in the diesel particulate filter (DPF) core. Thus, after the post-service tests, the unit was renewed with a fresh OEM spare part, and as the final result of these test with diesel cars, results obtained in tests after the DPF was changed to a new unit, are presented in Figure 5-12.

The Figure shows that while both PM and PN were effectively cut down – as expected, HC and especially CO were higher after the repair, while NOx and CO_2 were not much different. Even with these untoward changes, the improvement in particulates was very significant, as the PM level was dropped by a factor of 10 (-86% to -88%), and PN even more, with a factor of over 60 (-98% to 99%).

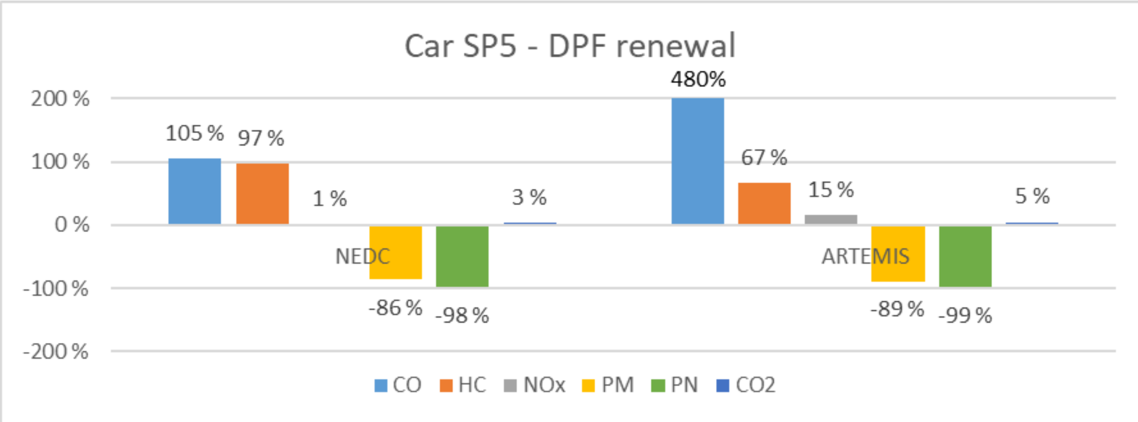


Figure 5-12: Relative change in exhaust emissions with NEDC (left stack) or ARTEMIS Urban (right stack) test cycles, Car SD5 after a faulty DPF was changed to a new

6. Summary and conclusions

6.1 Exhaust emission measurements

The exhaust emission measurement campaign conducted in Task 3.1 with six passenger cars driven by a pool of fifteen drivers on a single route provided a good set of accurate measurement results to be used in developing the equations that describe the relationships between driving parameters and different emissions species. This was ascertained by the analysis presented in this Deliverable, and further elaborated as described in Deliverable D3.2.

The driver pool consisting of drivers between 30 and 64 years of age and both genders, and their driving experience ranged from 12 to 44 years. They were drafted amongst the employees of VTT, and with some exceptions they all drove four petrol-fuelled and two diesel-fuelled cars. The test route was about 30 km long and was composed of mainly urbans streets but included also sections of rural-type road, motorway and dual carriageway type of main artery. Each test driver drove the route two times in succession, with only a short pause in between.

The high-level analysis based on the main descriptive parameters of driving (average speed, average engine speed, total work over trip) and the resulting fuel consumption, as well as measured levels of exhaust emissions revealed that amongst the drivers, there were distinctly some drivers that were able to constantly drive with low emissions output, while retaining also low fuel use. On the other hand, there were also some drivers that drove with high emissions and used a lot of fuel, and whose driving was also less consistent. This provided a good standpoint on developing the description of "low emissions driving" to be used in the guidelines developed in WP5.

6.2 Brake emissions measurements

Task 3.2 included a novel way of accurately measuring, how the way of applying the brake affects to the amounts of brake particulates dissipating from the brake. It was based on the latest version of the common inter-laboratory methodology to independently measure non-exhaust brake-related emissions in terms of particle matter (PM) and particle number (PN), developed in the PMP Particle Measurement Informal Working Group under the UNECE umbrella, and was implemented in the Brembo brake dynamometer test setup, which was one of the test set-ups that have been used to develop such methodology.

To address the role of the drivers and their driving behaviours on brake emissions, some modifications were applied to this reference cycle, in order to reproduce a more conservative driving and braking progression. For this purpose, some of the braking events were modified according to the guidelines for low emission driving reported in D5.1. In particular, the simulated vehicle decelerations and the initial braking speed of the most demanding stops have been reduced. All these modifications simulate a higher attention of driver to the traffic situations, and thus lead to a more conservative driving behaviour with less use of brakes. Furthermore, with the aim of replicating the same trip, the total length travelled by the vehicle over the test cycle, and the number of the braking events have all kept equal to the reference WLTP-Brake.

From the experimental activity carried out during T3.2 it was clear that a significant reduction in the emissions coming from the wear of the braking components could be achieved with a more conservative driving behaviour.

6.2 Tyre emissions measurements

In Task 3.3 tyre wear emissions were addressed. As it is very challenging and difficult to measure, how the tyre emits particles due to the abrasion of the road surface, the relationship between driving behaviour and tyre wear, resulting in particulate emissions, were addressed with an on-road test campaign. For this purpose, a pool of drivers was recruited from Rome and Milan in Italy, and Athens in Greece, and a total of 76 drivers and their vehicles participated. With the aid of an OBD dongle and associated on-board data acquisition system, characteristic driving parameters were continuously measured and recoded during driving and collected in a cloud server. The most important parameters were longitudinal and lateral acceleration, as well as speed of the vehicle. Tyre wear was recorded with measuring the depth of tyre grooves with three-month intervals, and the loss of material was subsequently calculated.

A clear difference was found in tyre wear between front and rear tyres, mainly due to the fact that all participating cars were front-wheel driven, which tends to put much more load on the front tyres, because they are responsible for both traction (longitudinal loads) and steering (lateral loads), whereas the rear wheels are just “free rolling” with much less forces applied. Apart from this quite obvious result, the effect of vehicle make/model and tyre size was also addressed, as well as different types of tyres (compounds).

The analysis revealed that tyre wear measurements vary substantially between tyre positions, vehicle types, tyre sizes as well as tyre types, and the collected data contained a considerable number of outliers. As the fleet size was quite limited, it was not clear whether this variability was acceptable and genuine, and caused by the different local road and environment conditions or was resulting from errors in the measurements. This also suggested that if the important factors in the driving behaviours, which result in outlier measurements, are not known, predictive models for simulating the tyre wear may not perform well.

Nonetheless, an attempt was made to quantify the link between tyre wear and driving behaviour by modelling. The work started by taking only a few major driving behaviour parameters and using a simple linear regression model for tyre wear prediction, and taking the average values for longitudinal accelerations, lateral accelerations and vehicle speeds as independent variables. However, this led to a poor correlation, indicating that the average values of longitudinal and lateral accelerations as well as vehicle speed cannot explain the variability of tyre wear measurements. Therefore, a more complex, non-linear modelling was implemented, with a more sophisticated non-linear fitting method based on machine learning, including classification, regression, and ranking tasks. As the result of this exercise, an adequate level of understanding about the relative importance of featured parameters affecting tyre wear rates was achieved.

6.4 Effect of service and maintenance

The effect of service on exhaust emissions was studied with two pools of cars consisting of six petrol-fuelled and five diesel-fuelled models. Two cars were originally type approved by EU4 regulations, and the rest represented various levels of EU5. All cars were tested using both a legislative cycle (NEDC) and a non-legislative, real-world type of cycle (ARTEMIS Urban). Cars were tested prior to the service, and shortly after service and maintenance was applied to them. The service included change of motor oil and filter, as well as change of intake air induction filter. For petrol-fuelled cars, spark plugs were also renewed to maximise the effect of service, even if the service schedule was not calling it.

The results of this work showed that applying service and maintenance did not univocally meant lower exhaust emissions and/or fuel consumption, as expected. Moreover, the results varied highly between cars, emission components and test cycles. However, petrol-fuelled cars responded overall more positively than those with diesel engines, even if the diesel-fuelled cars had on average much higher odometer readings from close to 200 000 km up to almost 330 000 km than the petrol-fuelled ones, where even the highest of the pool was below 200 000 km, and others a lot lower. This led to a conclusion that modern engine management is able to maintain proper performance even if the regular maintenance schedule is not closely followed. However, this does not mean that service and maintenance are not important, because they may reveal such malfunctions that can lead to high emissions, even if we could not encounter such cases in this exercise.

7. References

[1] GRPE-81-12 Informal document, “Non-Exhaust Brake Emissions – Laboratory testing – Part 1: Inertia Dynamometer Protocol to Measure and Characterise Brake Emissions Using WLTP-Brake Cycle”, 81st GRPE, 9-11 June 2020, Agenda item 7,

https://unece.org/fileadmin/DAM/trans/doc/2020/wp29grpe/GRPE-81-12e.pdf;

[2] ECE/TRANS/505/Rev.1/Add. 48/ Rev.7, Regulation no. 49;

[3] ECE/TRANS/505/Rev.1/Add.82/Rev.5, Regulation no. 83;

[4] Mathissen Marcel, Grochowicz Jaroslaw, Schmidt Christian, Vogt Rainer, Farwick zum Hagen Ferdinand, Grabiec Tomasz, Steven Heinz, and Grigoratos Theodoros. "*WLTP-Based real-world Brake Wear Cycle*"; DOI: 10.17632/dkp376g3m8.1.

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Adapting driver behaviour
for lower emissions

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 815189.