POLITECNICO DI TORINO

Master of Science in Mechanical Engineering
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RDE TEST ANALYSIS :
REGULATION, MATLAB TOOL TO POST PROCESS TEST DATA AND NOX EMISSIONS ANALYSIS

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Abstract

The concern about vehicle emissions and air pollution has increased in the last years and it has caused the born of new regulations which are influencing powertrains development.
A new more realistic homologation test procedure has been introduced in order to reduce the differences between laboratory test (NEDC and WLTC) and real driving emissions: the RDE test.
Because of its high variability, RDE procedure has introduced new challenges and complexity on today's approach for the development of vehicles and engine.
The aim of this work is to define and validate a matlab tool able to analyze and post process RDE tests data to determine if a valid test has been done and to quantify pollutant emissions.
In order to achieve this goal, firstly, a deep analysis of present and future RDE regulation has been performed to understand how to do in practice an RDE test and which are the parameters and the calculations that shall be considered to validate a trip and evaluate its pollutant production.
Secondly, the matlab tool created has been validated comparing its results with Emroad (JRC* official software) and Horiba (PEMS* renting company) considering the same input information.
Finally the matlab tool has been modified in order to receive input information only from vehicle sensors to perform and analyze an RDE test without the need of the PEMS.
The last part of this work, instead, deals with a detailed NOx analysis performed to understand trip, driving, ambient and engine conditions which are more severe for NOx emissions in a diesel engine vehicle.

*JRC = Joint Research Centre
PEMS = Portable Emission Equipment System

Astratto

L'interesse riguardo l'impatto sull'atmosfera e sulla salute umana delle emissioni di inquinanti prodotte dai veicoli è cresciuto sempre di più negli ultimi anni e ha causato la nascita di nuove normative che hanno influenzato e influenzeranno lo sviluppo dei motori automobilistici.
Una nuova procedura di omologazione più realistica è stata introdotta per ridurre le differenze ingenti presenti tra le emissioni ottenute in laboratorio (NEDC e WLTC) e quelle misurate durante la guida nel traffico reale: il test RDE.
A causa della sua elevata variabilità, tale procedura introduce nuove sfide e maggiore complessità nello sviluppo dei veicoli e dei rispettivi motori.
L'obiettivo di questo studio è di definire e validare un programma matlab in grado di analizzare e processare dati di un test RDE per determinarne la sua validità e quantificarne le emissioni prodotte.
Al fine di raggiungere tale scopo, prima di tutto, è stata analizzata approfonditamente la normativa presente e futura per capire come condurre, nella pratica, un test RDE e quali parametri e calcoli devono essere sviluppati per una sua completa analisi.
In secondo luogo, il codice matlab è stato validato comparandone i risultati con Emroad (software ufficiale JRC) e Horiba (una delle compagnie che produce il PEMS) considerando per i tre software le stesse informazioni di partenza, ovvero parametri misurati dagli analizzatori del PEMS durante il test.
In conclusione tale codice è stato modificato in modo da ricevere come dati di partenza informazioni provenienti dai sensori dell'automobile al fine di poter eseguire un test RDE senza la necessità di affittare il PEMS da compagnie esterne.
Nell'ultima parte di tale lavoro, infine, è stata svolta una dettagliata analisi delle emissioni di NOx misurate durante diversi test condotti con un veicolo diesel al fine di indagare quali condizioni, che si possono verificare durante un test RDE, sono le più pericolose in termini di inquinamento considerando diversi percorsi, stili di guida e condizioni atmosferiche.

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Regulation

Introduction

In road transport regulation is fundamental.
His aim is to limit pollutant and greenhouse gases emitted by vehicles to improve air quality and decrease their negative impact on human health and global warming.
It is really important because it leads the research to develop car technologies, in particular about the internal combustion engine and the after-treatment system.
Regulation establishes maximum emission limits (in g/km) and methods that have to be implemented to measure them: this last point is particularly significant because it is in the process of change in these years.
Every vehicle, before its market introduction, have to respect these limits in a reference cycle.
The characteristics of a good pollutant measuring method are to represent the most frequent operating condition of a powertrain and to measure pollutant with accuracy and precision.
From September 2017, with the entry into force of EURO 6d-TEMP, two new cycles have been introduced to measure emissions in a more realistic way: WLTC and RDE.
WLTC (Worldwide Harmonized Light Vehicles Test Cycles) has been introduced in order to replace NEDC (New European Driving Cycle) which had some significant differences compared to real driving style: it was characterized by low acceleration, constant speed cruising and high number of idling events which didn't represent real transient accelerations and caused huge differences compared to real driving emissions.
WLTC, on the contrary, is distinguished by a more aggressive driving style, an use of the engine which covers a bigger portion of points of its map and the power on of some accessories such as headlights or conditioned air that brings it closer to reality.
The main problem is that WLTC is still a test done in a laboratory with limited ambient conditions, a precise driving style and a flat road: so it covers only a small part of the amount of total conditions that can occur during the real drive.
A proof of this consideration is that emissions measured during the laboratory tests are very different from on-road emission: for this reason WLTC is now flanked by a new cycle, the RDE (Real Driving Emission), which is a test performed on-road in real world driving conditions using PEMS (Portable Emission Measurement System) to measure pollutant emissions.
RDE test is regulated by 'COMMISSION REGULATION (EU) 2017-1151 Consolidated – Annex IIIA' which describes which rules has to be followed to collect and process data for a valid RDE trip.
In fact, the main difference with previous regulatory cycles is that it doesn't exist an unique RDE cycle but every test, that satisfies all the requirements defined in the regulation, can be considered a valid RDE cycle.

NTE limit

The starting point of the regulation is to define the NTE (Not To Exceed) limit for each pollutant taken in account:

$$NTE_{pollutan} \; = CF_{pollutant} \, x \, TF(p_1, \dots p_n) \, x \, EURO6_{limit}$$

Where:

- $NTE_{pollutant}$ is the limit that each pollutant has not to exceed in a RDE test to make the vehicle been approved (in case of type approval); it has to be respected also during the total lifetime of the vehicle (in case of in-service conformity since pack 4);

- $CF_{pollutant}$ is a conformity factor introduced to soften the impact of change from NEDC to RDE method and to take into account the inaccuracy of the PEMS.
  It is different for PN and NOx:
  - ✓ CF_{PN} = 1.5 = 1 + 0.5 (PEMS inaccuracy)
  - ✓ CF_{NOx}:
    - 2.1 = 1 + 0.5 (PEMS inaccuracy) + 0.6 (margin) until January 2020 for new types and January 2021 for new vehicles (RDE Step1);
    - 1.5 = 1 + 0.5 (PEMS inaccuracy) from January 2020/2021 (RDE Step2);

  This factors could be changed in the following versions of the legislation if there will be improvements in PEMS measurement.

- $TF(p_1, \dots p_n)$ is a transfer function that, generally, is set to 1 for the entire range of parameters $(p_1, \dots p_n)$, but it could be modified without damaging the effectiveness of the RDE test procedures, if this condition is satisfied:

$$\int TF\ (p_1, \dots p_n)\ x\ Q\ (p_1, \dots p_n)\ dp = \int Q\ (p_1, \dots p_n)\ dp$$

  Where Q is the probability of density of an event corresponding to the parameters in real driving and dp is the integral over the entire space of the parameters.

- $EURO6_{limit}$ is the pollutant limit established by WLTC regulation

			RDE Step 1 (EURO6d – TEMP)		RDE Step 2 (EURO6d)	
			Gasoline	Diesel	Gasoline	Diesel
NOx	EURO6limit	mg/km	60	80	60	80
	NTE	mg/km	126	168	90	120
PN	EURO6limit	mg/km	$6 * 10^{11}$	$6 * 10^{11}$	$6 * 10^{11}$	$6 * 10^{11}$
	NTE	mg/km	$9 * 10^{11}$	$9 * 10^{11}$	$9 * 10^{11}$	$9 * 10^{11}$

Table 1 – Regulation - Euro 6 Emission limits

Trip requirements

As it was said before, RDE trip is not unique, repeatable and characterized by fixed values of distance and speed, but it is considered valid if it satisfies a list of conditions fixed in the regulation.
For vehicles belonging to category M1, all the conditions can be summarized as follows:

Driving portion		Urban	Rural	Motorway
Speed	km/h	[0 ; 60]	[60 ; 90]	[90 ; 160]
Minimum distance	km	16	16	16
Distance share	%	[29 ; 44]	[23 ; 43]	[23 ; 43]
Total duration	min	[90; 120]		
Total stop time (v < 1km/h)	%	[6 ; 30] Urban time	-	-
Single stop time	s	< 300	-	-
Average speed (including stops)	km/h	[15 ; 40]	-	-
Maximum Speed	km/h	-	-	[110 ; 160]
Speed > 100 km/h	min	-	-	≥ 5
Speed > 145 km/h	%	-	-	< 3% Motorway time
Start / End test elevation difference	m	≤ 100		
Cumulative Positive Elevation Gain	m/km	< 1200 m / 100 km (for only urban part & total trip)		

Table 2 - Regulation - RDE General trip requirements

Cold start	Average Speed	km/h	[15 ; 40]
	Maximum Speed	km/h	60
	Stop time	s	≤ 90
	Idling (engine speed <1000 rpm) after first ignition of the combustion engine	s	≤ 15

Table 3 - Regulation - RDE Cold start requirements

Each point of the trip is divided in urban, rural and motorway section based on its speed as specified in the table. According the regulation the trip has to start with a urban part followed by rural and motorway: rural part could be interrupted by an urban part and motorway by an urban or rural portion indifferently but, at the end, each part has to be characterized by, at least, 16 km with an opportune distance share.
Another important condition is about the stop period (time with vehicle speed less than 1 km/h): it is taken in account in the urban part (speed ≤ 60 km/h) and it has to be inside a precise interval: to join this condition it is usual, during the urban part of an RDE trip, to stop for some seconds on the roadside.
Regulation fixes speed rules, too: in particular vehicle speed has to join at least 110 km/h and at maximum 160 km/h: exceed legal speed limits doesn't invalid an RDE test.
Moreover speed has to be higher than 100 km/h for at least 5 minutes: this rule was introduced to avoid RDE trip not so aggressive created to decrease emissions.
Finally, two interesting and important conditions involve the allowed positive cumulative elevation gain and the cold start.
In the regulation there is a precise procedure which has to be followed to calculate the elevation gain based on three parameters: h_{GPS} (instantaneous vehicle altitude measured by GPS), v_i (instantaneous vehicle speed) and t (time passed since test start).
First of all it is necessary to check if these data are complete. If no, they shall be corrected by interpolation using a topographic map.
Secondly a correction based on vehicle speed of each point shall be applied to obtain a valid set of altitude data.
Then the calculation of the cumulative positive elevation gain can be done: instantaneous distance has to be evaluated and has to be used to smooth the altitude data obtained for each discrete point by applying a two-step procedure achieving a final value of road grade for the considered point. Then all the positive interpolated and smoothed road grades shall be integrated and normalized by the total test distance.
This calculation has to be done for total trip and for only urban part, too.

Regarding cold start, which is really important because pollutant emission produced in this phase are taken in account in the evaluation of the total amount, there are conditions about average and maximum speed and stop time.
Regulation defines the cold start as '*the period from the first start of the combustion engine until the point when the combustion engine has run cumulatively for 5 min. If the coolant temperature is determined, the cold start period ends once the coolant has reached 343 K (70 °C) for the first time but no later than the point at which the combustion engine has run cumulatively for 5 min after initial engine start*' (COMMISSION REGULATION (EU) 2017-1151 Consolidated – Annex IIIA – Appendix IV): it has been noticed, by experiment, that time limitation is prevailing on coolant temperature limitation because an engine spends about 600 s to join 70degC (even if this value is highly dependent on ambient condition and tested cars).
In order to satisfy all these conditions RDE trips have to be well defined before taking into account of all the possible real situations that could be found during the trip (traffic, roadworks, traffic lights, weather) considering that regulation established that RDE tests shall be conducted on working day and on paved road and streets.
In my opinion a fundamental choice that has to be done is the approach we want to use about the fulfilment of criteria: in my work I tried to be in the middle of intervals to be sure not to invalidate the trip.
I think that defined a RDE trip based on worst conditions is not a good choice because it obliges cars manufacturers to overestimate after-treatment systems increasing a lot costs to fulfil criteria which happen rarely.

Boundary Conditions

In order to perform a valid RDE test attention need to be paid to boundary conditions: they are related to vehicle payload and test mass, temperature, altitude, vehicle conditioning for cold engine-start, auxiliary systems and dynamics.
Regulation, in fact, fixes general rules for each of these fields to avoid rare conditions and particular driving style.

- *Vehicle payload and test mass*

  The vehicle's basic payload shall comprise the driver, a witness of the test and the test equipment (PEMS, power supply and mounting devices).
  For experimental purposes load can be increased until:

$$Basic\ Payload + Added\ Load \leq 90\ \%\ (Mass\ of\ the\ passengers + paymass)$$

  Pay mass = technically permissible maximum laden mass – mass in running order – mass of passengers – mass of optional equipment.

- *Ambient conditions: altitude & temperature*

  Regulation classifies ambient conditions in normal, extended and not valid.

  - ✓ Moderate conditions:
    - Altitude: [0 ; 700] m
    - Temperature: [0 ; 30] degC from January 2020 for new types and January 2021 for new vehicles
      (before this date [3 ; 30] degC)
  - ✓ Extended conditions:
    - Altitude: [700 ; 1300] m
    - Temperature: [-7 ; 0] & [30 ; 35] degC
      (before 2020 - 2021 [-2 ; 3] & [30 ; 35] degC)
  - ✓ Not valid conditions:
    - Altitude: > 1300 m
    - Temperature: < -7 degC & > 35 degC
      (before 2020 - 2021 T< -2 degC & T> 35 degC)

  For each point, if it is in extended conditions, specific pollutant raw emissions of that point have to be divided for 1.6 (not for CO_2 emissions).
  This coefficient shall be applied for every cold start points if moderate condition are present at the beginning of the test but severe conditions are present for three hours before its start.

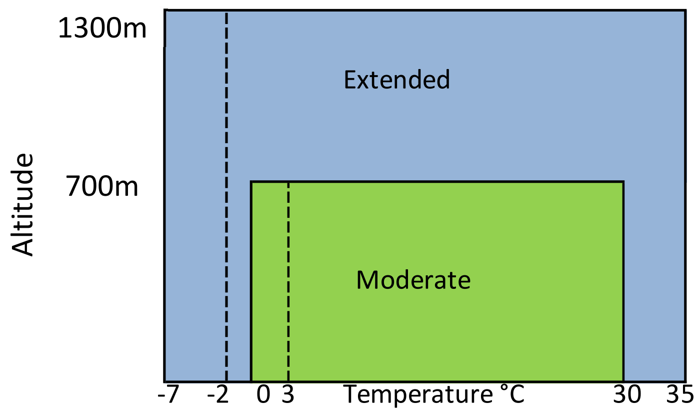


Figure 1 - Regulation - RDE Extendend boundary conditions

- *Preconditioning*

  The vehicle shall be driven for at least 30 minutes and then parked with doors and bonnet closed and kept in engine-off status in moderate or extended altitude and temperature conditions between 6 and 56 hours before the test.
  Extreme atmospheric condition shall be avoided.
  If a previous RDE test is done it is considered as preconditioning as long as time the amount of hours of engine-off status is respected.

- *Auxiliary system*

  The air conditioning system or other auxiliary devices shall be used as a consumer at real driving on the road would use them.

- *Dynamic conditions*

  They are introduced to take into account the effect of road grade, auxiliary system and driving dynamics (accelerations and decelerations) upon the emissions of the vehicle.
  The verification of these conditions has to be done in three steps.

  - <u>Determination of $v{*}a_{pos}$ [95] and RPA</u>

    These two methods are used to check the overall excess or insufficiency of driving dynamics during the trip: their aim is to prevent too calm or too aggressive trips.
    First of all data shall be collected with a sampling frequency of 1 Hz, then all the points have to be classified with positive acceleration (higher than 0.1 m/s^2) in urban, rural and motorway bins based on their speed (same limits used for trip requirements): to have a valid test each bin shall contain at least 150 points.

After this first check v*a_{pos} [95] and RPA calculation shall be done for each group. v*a_{pos} [95] is the 95th percentile of the product of vehicle speed per positive acceleration: for each point, starting with their speed, their distance increment and their acceleration is determined and the product of vehicle speed per acceleration is computed:

$$d_i\ [m] = \frac{v_i\ [km/h]}{3.6}$$

$$a_i\ [m/s^2] = \frac{(v_{i+1} - v_{i-1})\ [km/h]}{2 * 3.6}$$

$$(v * a)_i\ [m^2/s^3] = \frac{v_i[km/h] * a_i[m/s^2]}{3.6}$$

Later they are ranked $(v*a)_i$ in ascending order and for each bin the percentile is calculated: the lowest value gest the percentile 1/M_k (M_k is the total number of samples with positive acceleration for each bin) (k = urban, rural or motorway), the highest M_k /M_k (100 %).
In this way the value with j/ M_k = 95 % is defined. If it is not present, it is calculated by linear interpolation between consecutive samples j (j / M_k < 95%) and j + 1 ((j+1) / M_k >95%).
For each bin the determined value shall be lower than a maximum value defined by regulation based on their average speed (based on the total number of samples, not only points with positive acceleration).

	v ≤ 74.6 km/h	v > 74.6 km/h
MAX v*a_{pos} [95] [m^2/s^3]	0.136 * v + 14.44	0.0742 * v + 18.966

Table 4 – Regulation - RDE va_{pos} [95] conditions*

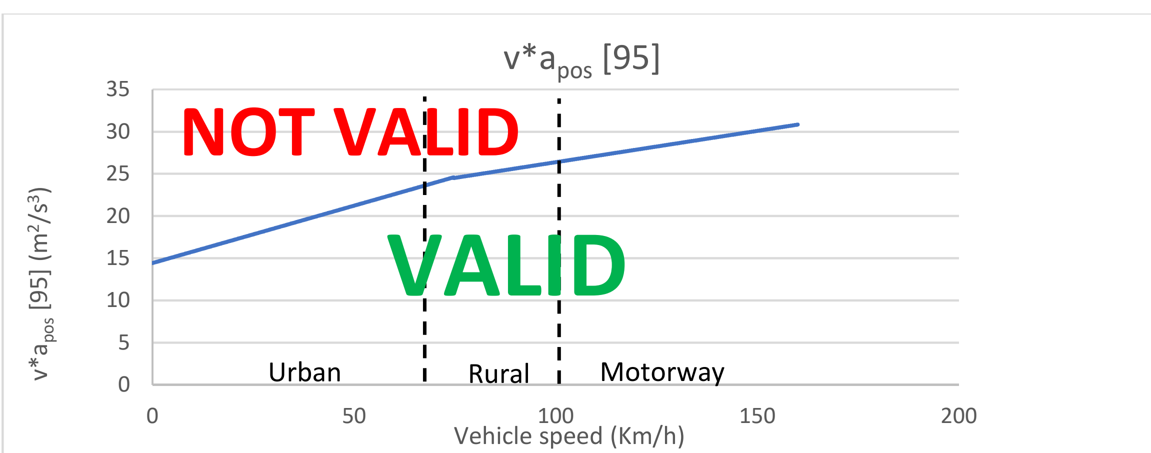


Figure 2 - Regulation - RDE va_{pos} [95] graphic*

RPA is the relative positive acceleration of each point:

$$RPA_k\,[m/s^2] = \frac{\sum_{j=1}^{M_k}\left[\Delta t * \left(v * a_{pos}\right)_j\right]}{d_{TOT,k}}$$

Where:

- k = urban, rural or motorway (RPA has to be calculated, as $v{*}a_{pos}$ [95], for each bin)
- Δt is the time difference (equal to 1s because sampling frequency = 1 Hz)
- M_k is the total number of samples with positive acceleration for each bin
- $d_{TOT,k}$ is the total distance of each bin calculated for all the points (not only points with higher positive acceleration)

For each bin, RPA value shall be higher than a minimum value defined by regulation based on their average speed (same average speed used for $v{*}a_{pos}$ [95]).

	v ≤ 94.05 km/h	v > 94.05 km/h
MIN RPA $[m/s^2]$	- 0.0016 * v + 0.1755	0.025

Table 5 - Regulation - RDE RPA conditions

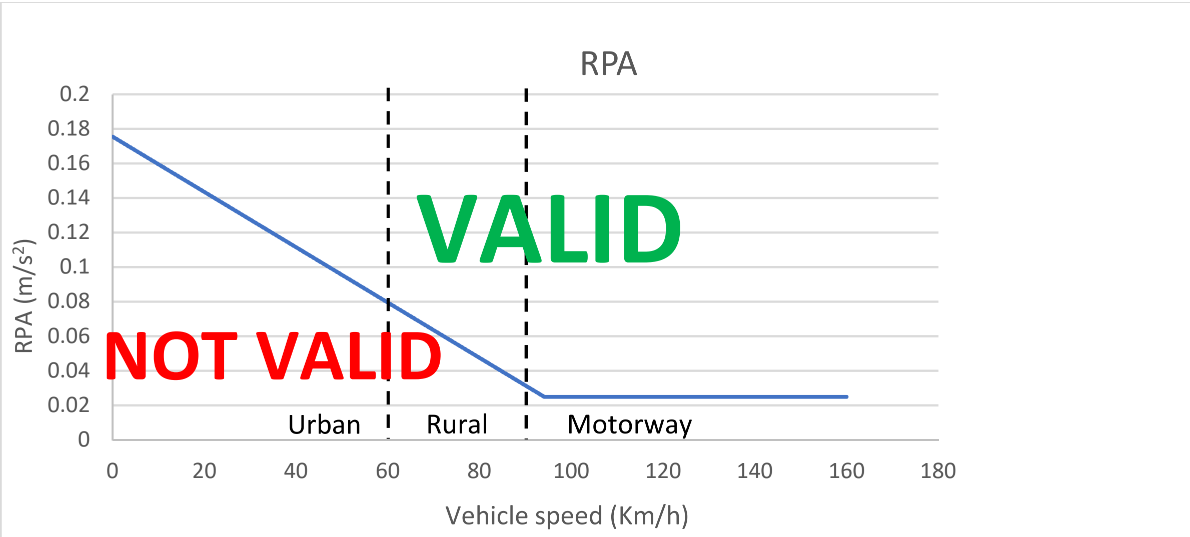


Figure 3 - Regulation - RDE RPA graphic

- <u>MAW</u>

MAW (Moving Average Window) method is a statistical method used to validate an RDE test and to evaluate data.
This chapter deals with its utilization to establish the validity of a test.
This method consists in dividing the entire trip into sub-sections and in analyzing the total number of urban, rural and motorway windows to define if each window is normal comparing its CO_2 distance-specific emission with a reference curve.
In the application of this method data which correspond to periodic verification of instruments and data with vehicle ground speed < 1 km/h shall not considered for the calculation of the CO_2 mass, the emission and the distance of averaging windows.
First of all windows are defined such that for each window the vehicle produces the same mass quantity of CO_2 (equal to 50 % of CO_2 produced by the same vehicle during a WLTC).
So the first window starts at the beginning of the test and last until CO_2 reference mass has been produced, the second window starts one second after the beginning of the first one and ends when it reaches the same value of CO_2 produced and so on until it is not possible anymore define windows that produce the total amount of CO_2 reference value.
In this way each window has its own distance and time duration dependent on driving condition (for example, in motorway instantaneously more CO_2 is produced and so windows have lower time duration).
Secondly, for each window, its average speed is calculated to classify them in urban, rural and motorway paying attention to speed limits because they are different:

- Urban : v < 45 km/h
- Rural : 45 km/h < v < 80 km/h
- Motorway : v > 80 km/h

This classification appears in contrast with the limits established before for the urban, rural and motorway shares: this is not true because they take into account the average speed of a window started from the beginning of the trip as for the distance share they take into consideration the instantaneous vehicle speed.
In a document of European Commission it is written that "*our experience suggests that if the requirements of point 6.6 regarding the urban, rural, motorway shares* [60,90 km/h] *are met, the averaging window speeds typically fall within the value ranges specified in Appendix 5* [45,80 km/h]" (QA RDE vs2b).

RDE test is valid if at least 15 % of total windows are urban, 15 % are rural and 15 % are motorway windows (**completeness check**).

Thirdly, for each window the CO_2 distance – specific emission (g/km) in respect of their average speed is computed and compared with a reference curve.

Reference curve is made by two linear interpolation done between three different points defined as follow:

- P_1 (19.0 km/h ; 1.2*CO_2 vehicle emissions in WLTC low speed phase)
- P_2 (56.6 km/h ; 1.1*CO_2 vehicle emissions in WLTC high speed phase)
- P_3 (92.3 km/h ; 1.05*CO_2 vehicle emissions in WLTC extra-high speed phase)

Two tolerance areas are defined: the first one ± 25 % distant from the reference curve, the second one ± 50 %.
RDE test is valid if at least 50 % of urban, 50 % of rural and 50 % of motorway windows are inside the first tolerance (**normality check**).
If these conditions are not satisfied the first up tolerance could be increased 1% at a time until it reaches a maximum value of 30 % (as the first down tolerance is fixed to 25% and it can not be changed).
If this value is reached and there is still not the presence of at least 50 % of windows for each bin inside the first tolerance, the test is not valid.
The second tolerance is used for data evaluation as it will be explained in the next chapter.

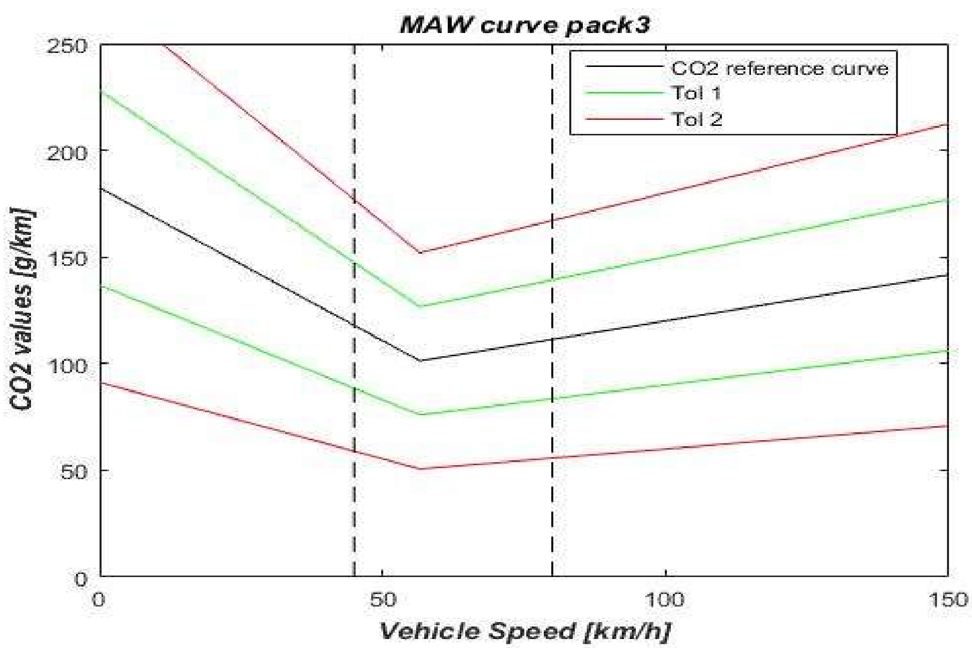


Figure 4 - Regulation - RDE PACK 3 MAW - Characteristic curve (example)

MAW method that it has been described so far is the one which is now in force (RDE pack 3). In the future RDE pack 4, this method will be modified as follow:

- ✓ P_1, P_2 and P_3 will have the same coordinate in x-axis (vehicle speed) but different one in y-axis (respectively CO_2 vehicle emissions in WLTC low speed phase, high speed phase and extra-high speed phase without any corrective factor);
- ✓ The first tolerance (green lines) will be - 25% for the lower case and + 45% for the upper case in the urban part and + 40% for rural and motorway without any possibility to increase them for ICE as for HEV these percentages can be increased up to 50 % : with this change it will be easier to satisfy MAW normality check;
- ✓ The second tolerance (red lines) will disappear because this method will be only used to validate the trip and not anymore to calculate emissions.

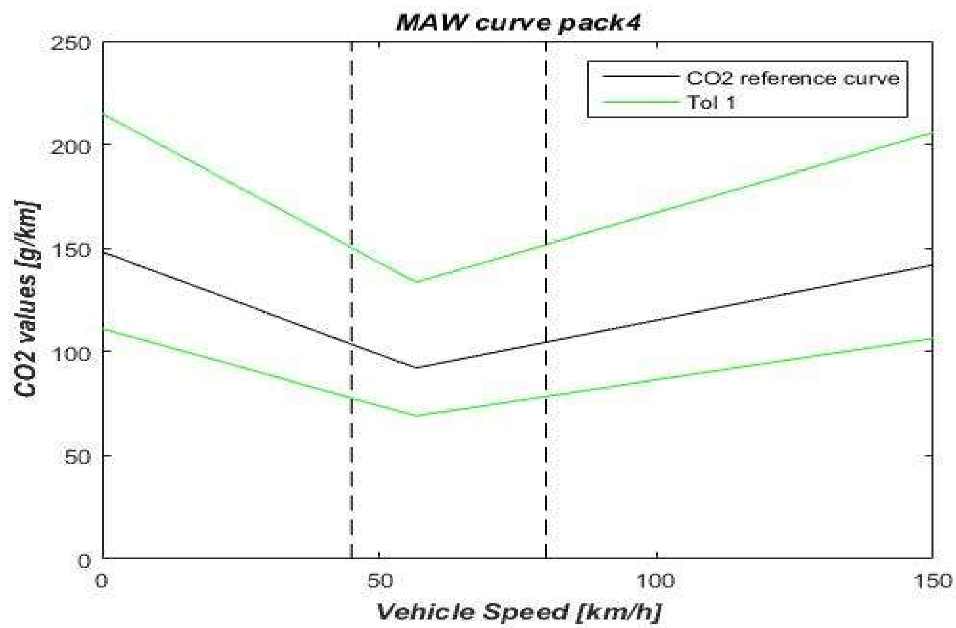


Figure 5 - Regulation - RDE PACK 4 MAW - Characteristic curve (example)

o <u>Power Binning</u>

This method aims to check if the vehicle uses the main part of its available power during an RDE trip: for this purpose all the points of the trip shall be classified in accordance with the corresponding power at the wheels.
Wheel power is defined by regulation as " *the total power to overcome air resistance, rolling resistance, road gradients, longitudinal inertia of the vehicle and rotational inertia of the wheels*" and it can be measured by a torque signal or determined by instantaneous CO_2 emissions.
In our case instantaneous wheel power was determined by CO_2 instantaneous values:

$$P_{w,i} = \frac{CO_{2,i} - D_{WLTC}}{k_{WLTC}}$$

With two additional conditions:

1. If $v_i \leq 1\ km/h$ and if $CO_2 \leq D_{WLTC}$ then $P_{w,i} = 0$
2. If $v_i > 1\ \ km/h$ and if $CO_2 < 0.5 * D_{WLTC}$ then $P_{w,i} = P_{drag} = -0.04 * P_{rated}$

Where k_{WLTC} [g/kWh] and D_{WLTC} [g/h] are the slope and the intercept of the Veline from WLTC and they are obtained by linear regression of CO_2 mass flow and wheel power of each phase of WLTC and P_{rated} [KW] is the maximum rated engine power as declared by manufacturer (see Matlab script for more details).

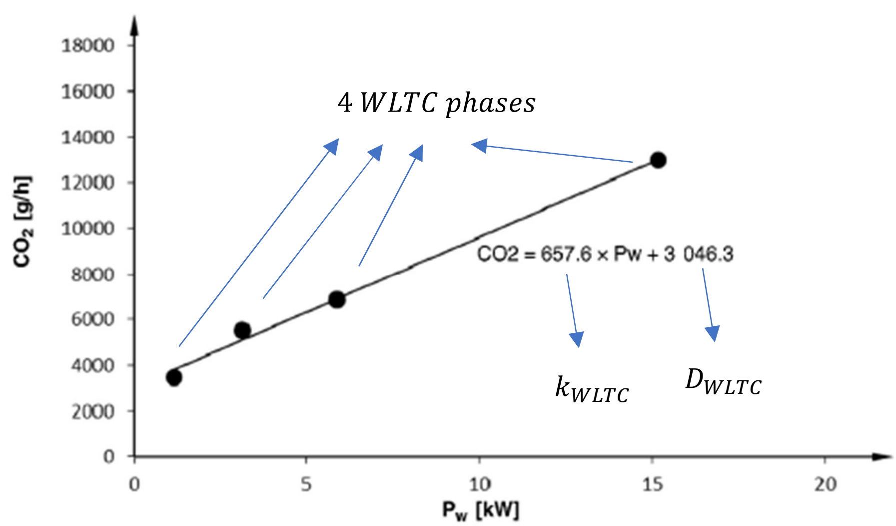


Figure 6 - Regulation - RDE PB - Vehicle specific veline from CO_2 WLTC results

Then wheel power has to be calculated for each point considering the three second moving average to reduce imperfect time alignment between emission mass flow and wheel power: after this calculation each point is sorted into the right de-normalized wheel power class present in the table.
In order to create this table, it is necessary to start by considering normalized standard power frequencies present in the regulation (Appendix 6 – Chapter 3.4) to de-normalize it multiplying each power value by P_{drive}.

Power class No	$P_{c,norm,j}$ [-]	
	From >	to ≤
1		− 0,1
2	− 0,1	0,1
3	0,1	1
4	1	1,9
5	1,9	2,8
6	2,8	3,7
7	3,7	4,6
8	4,6	5,5
9	5,5	

Table 6 - Regulation - RDE PB - Normalised standard power frequencies

$$P_{drive} = \frac{v_{ref}}{3.6}\ x\ (f_0 + f_1 x\ v_{ref} + f_2\ x\ v_{ref}^2 + T\ \ _{WLTP} * a_{ref})\ x\ 0.001$$

- v_{ref} = 66 km/h
- a_{ref} = 0.44 m/s^2
- f_0, f_1, f_2 are WLTP road load for the tested vehicle
- TM_{WLTP} is the WLTP test mass for the tested vehicle

Power class No	$P_{c,j}$ [kW]	
	From >	to ≤
1		− 1,825
2	− 1,825	1,825
3	1,825	18,246
4	18,246	34,667
5	34,667	51,088
6	51,088	67,509
7	67,509	83,930
8	83,930	100,351
9	100,351	

Table 7 - Regulation - RDE PB - De-normalized standard power frequency values (Example Pdrive = 18.25 kW)

The last condition that has to be checked is if the highest class includes 0.9*Prated (Prated is the maximum rated engine power as declared by the manufacturer).
If this condition is not satisfied the maximum power class to be considered is the highest class which includes 0.9*Prated and all the points characterized by higher values of $P_{w,i}$ shall be sorted in the highest considered class.
Power binning method shall be applied for the total trip and urban part taking in account that urban points are considered one with speed ranged from 0 to 60 km/h (different from MAW method).

RDE test is valid if:

- A minimum coverage of 5 counts is present for the total trip in each wheel power class up to class No 6 or up the class containing 90 % of the rated power whatever gives the lower class number;

- A minimum coverage of 5 counts is present for the urban part of the trip in each wheel power class up to class No 5 or up the class containing 90 % of the rated power whatever gives the lower class number.

Data evaluation

In order to evaluate pollutant emissions in RDE trip, three different methods can be used:

- MAW method (RDE pack 3, ongoing)
- Power Binning method (RDE pack 3, ongoing)
- Raw data (RDE pack 4, still to be voted)

MAW and Power Binning methods are not used only to validate the trip, but also to process data and evaluate pollutant emissions.
This is due to overcome the reproducibility issue of RDE test: each test is, in fact, really different to the others because of specific driving styles and environmental conditions.
With these two methods emissions are evaluated by a weighting average which normalizes cycles and makes them comparable reducing RDE test variability.

- <u>MAW</u>

In MAW method, first of all, a weighted average of the windows distance-specific emission (g/km) is determined separately for each portion (urban, rural and motorway) as follow:

$$M_{MAW,gas,k}\,[\frac{g}{km}] = \frac{\sum_j w_{j,k} * M_{gas,j,k}}{\sum_j w_{j,k}} \quad \text{(k = urban, rural or motorway)}$$

Where $M_{gas,j,k}$ is the distance-specific emission (g/km) of the jth window and $w_{j,k}$ is a weighting factor that has to be calculated for each window using these equations:

- If $M_{CO2}\left(v_j\right) * \left(1 - {tol_1}/{100}\right) < M_{CO2,j} < M_{CO2}\left(v_j\right) * \left(1 + {tol_1}/{100}\right)$
(window inside the area between the the two green lines) (figure N): $w_{j,k}$ = 1.
This means that points in this area have to been considered entirely;

- If $M_{COj2} < M_{CO2}\left(v_j\right) * \left(1 - {tol_2}/{100}\right)$ or $M_{CO2,j} > M_{CO2}\left(v_j\right) * \left(1 + {tol_2}/{100}\right)$
(window outside the area between red lines) (figure N): $w_{j,k}$ = 0.
This means that points in these areas have to been neglected because they are points with rare driving style;

- If $M_{CO2}\left(v_j\right) * \left(1 - {tol_2}/{100}\right) < M_{CO2,j} < M_{CO}\ \left(v_j\right) * \left(1 + {tol_2}/{100}\right)$
(window inside the area between the red lines): $w_{j,k} = \frac{1}{|tol_1 - tol_2|} h_j + \frac{tol_2}{|tol_1 - tol_2|}$
Where $h_j = 100 * \frac{M_{CO2,j} - M_{CO}\ (v_j)}{M_{CO}\ (v_j)}$ indicates how far we are from green and red lines.

The closer to green lines is a point, the higher (closer to 1) is the weighting factor. The closer to red lines is a point, the lower (closer to 0) is the weighting factor.

- If a window includes a cold start point: $w_{j,k} = 1$.

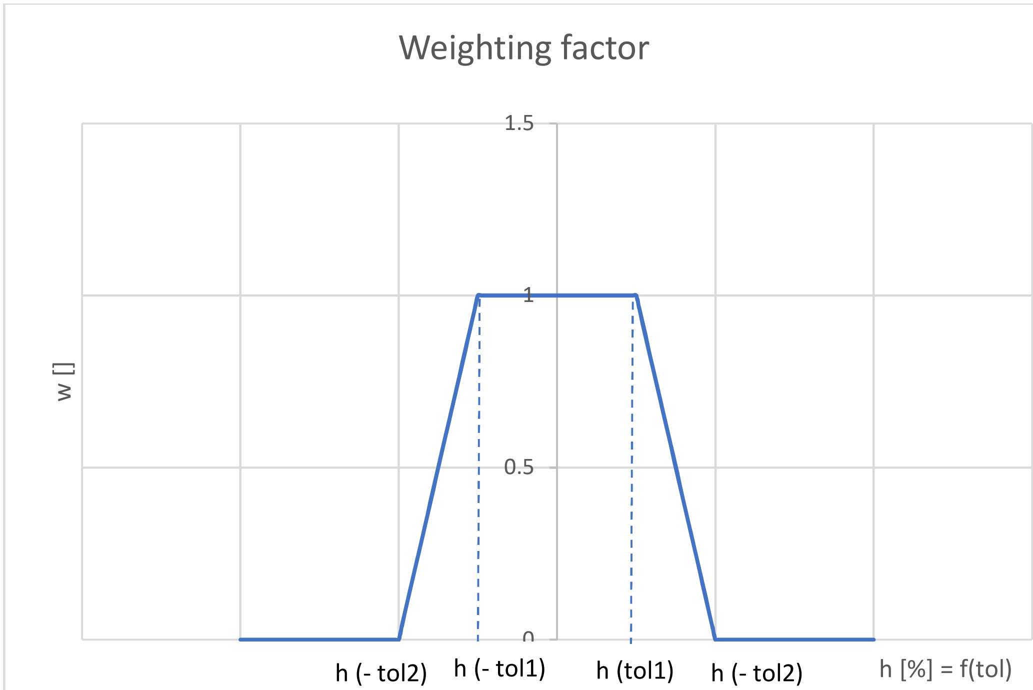


Figure 7 - Regulation - RDE MAW - Weighting factor

Using the previous formula distance-specific emission in g/km for each portion can be determined; then a weighted average is computed to evaluate the total distance-specific emission in mg/km:

$$M_{MAW,gas,t}\left[\frac{mg}{km}\right] = 1000 * \frac{f_u * M_{gas,u} + f_r * M_{gas,r} + f_m * M_{gas,m}}{f_u + f_r + f_m}$$

Where f_u, f_r and f_m are respectively equal to 0.34 , 0.33 , 0.33 regardless our trip distance share.

- Power Binning

According Power Binning method, specific emissions (g/s) and average speed for each wheel power class shall be calculated to define the weighting average considering a t_c for each class:

$$m_{gas,j}\ \left[\frac{g}{s}\right] = \frac{\sum_{s=1}^{j} m_{gas,s}}{counts_j}$$

$$v_j\ \left[\frac{km}{h}\right] = \frac{\sum_{s=1}^{j} v_s}{counts_j}$$

$$m_{gas}\ \left[\frac{g}{s}\right] = \sum_{j=1}^{9} m_{gas,j}\ x\ t_{c,j}$$

$$v\ \left[\frac{km}{h}\right] = \sum_{j=1}^{9} v_j\ x\ t_{c,j}$$

Where $counts_j$ is the number of elements for the j^{th} wheel power class and 9 is the total number of wheel power classes.

Finally the pollutant mass is divided for the speed to obtain the amount specific-emission distance for total and urban part:

$$M_{PB,gas,TOT}\ \left[\frac{mg}{km}\right] = \frac{m_{gas,TOT}\ x\ 3.6\ x\ 10^6}{v_{TOT}}$$

$$M_{PB,gas,u}\ \left[\frac{mg}{km}\right] = \frac{m_{gas,u}\ x\ 3.6\ x\ 10^6}{v_u}$$

- <u>Conclusion</u>

The vehicle is RDE compliant if both urban and total emissions are lower than NTE limit. So, one of these two couples of conditions shall be satisfied:

- $M_{MAW,gas,u} < NTE$ & $M_{MAW,gas,t} < NTE$
- $M_{PB,gas,u} < NTE$ & $M_{PB,gas,t} < NTE$

The main problem of this approach is that these two methods produce different emission results (2% - 30%) depending on the situation *('Comparison of Data Analysis Methods for European Real Driving Emissions Regulation'*).
For this reason, in Pack 4, these two methods will not be used anymore for data evaluation and they will be replaced by the calculation of raw data (ratio between the total mass of pollutant produced during the test and the total distance travelled) with a correction based on $CO2_{RDE}/CO2_{WLTP}$.
These two methods will remain applicable only for trip validation.

Different considerations have to be done for vehicles equipped with periodically regenerating systems (periodic regeneration required in less than 4000 km of normal vehicle operation, such as DPF regeneration): the regulation establishes, that if a regeneration occurs during an RDE test, results have to be avoided and test repeated. This can be done only for the first time: if, during the 2nd RDE test, regeneration occurs again, results shall be considered valid.
When there is a test without regeneration, final results have to be corrected with a K_i factor (> 1) to consider regeneration as a sum of small regenerations which happens during each test.
This is regulated in order to avoid that vehicles are calibrated to produce high quantity of NOx during regeneration taking advantage that, when it occurs, RDE test results are avoided.
In order to define K_i factor, there is a procedure explained in Sub-Annex 6 of Regulation, based on WLTC with and without regeneration: we have to calculate the increase of emission caused by regeneration and how often it occurs to consider the single contribution for each RDE test.
The application of Ki factor can be avoided if car manufacturers show that the vehicle is able to respect emission limits even if regeneration occurs.

RDE roadmap

The transition from NEDC to WLTC & RDE is happening in these years: for this reason boundaries conditions and corrective factors applied to emission results are still changing.
To resume the situation two timelines can be considered: they are referred to diesel new types (new car with new engine) and diesel new vehicles (all the car produced).

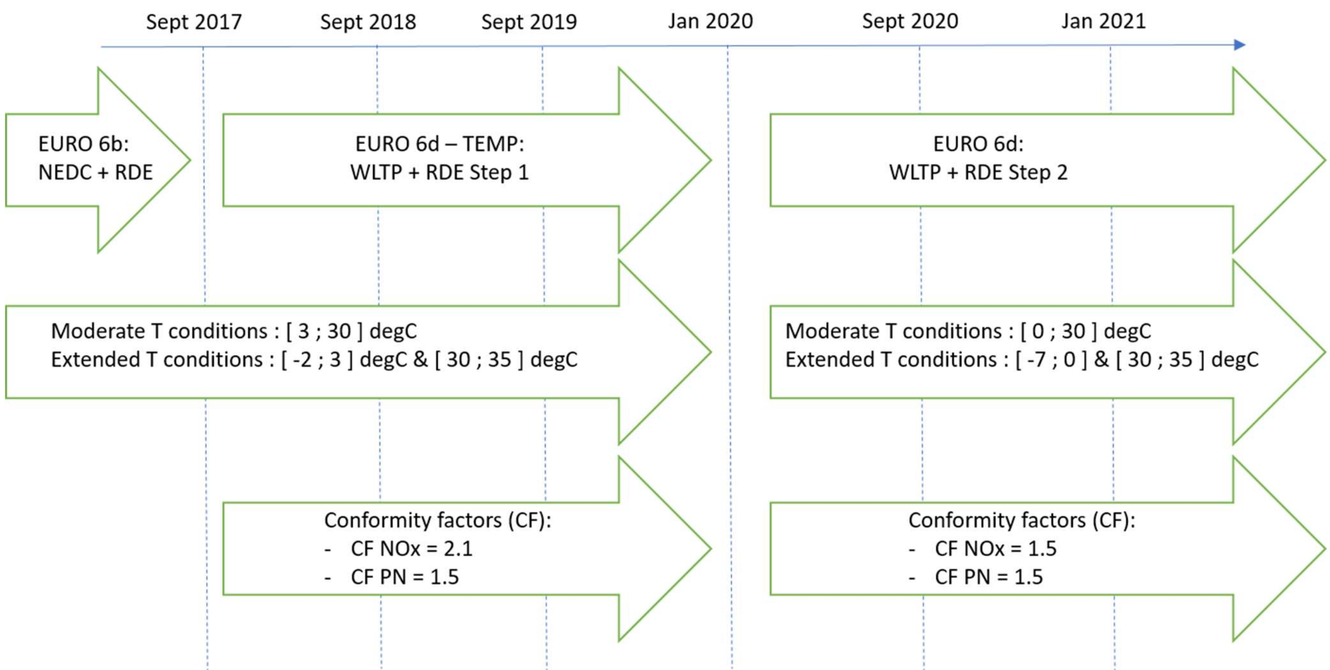


Figure 8 - Regulation - RDE Roadmap - New types

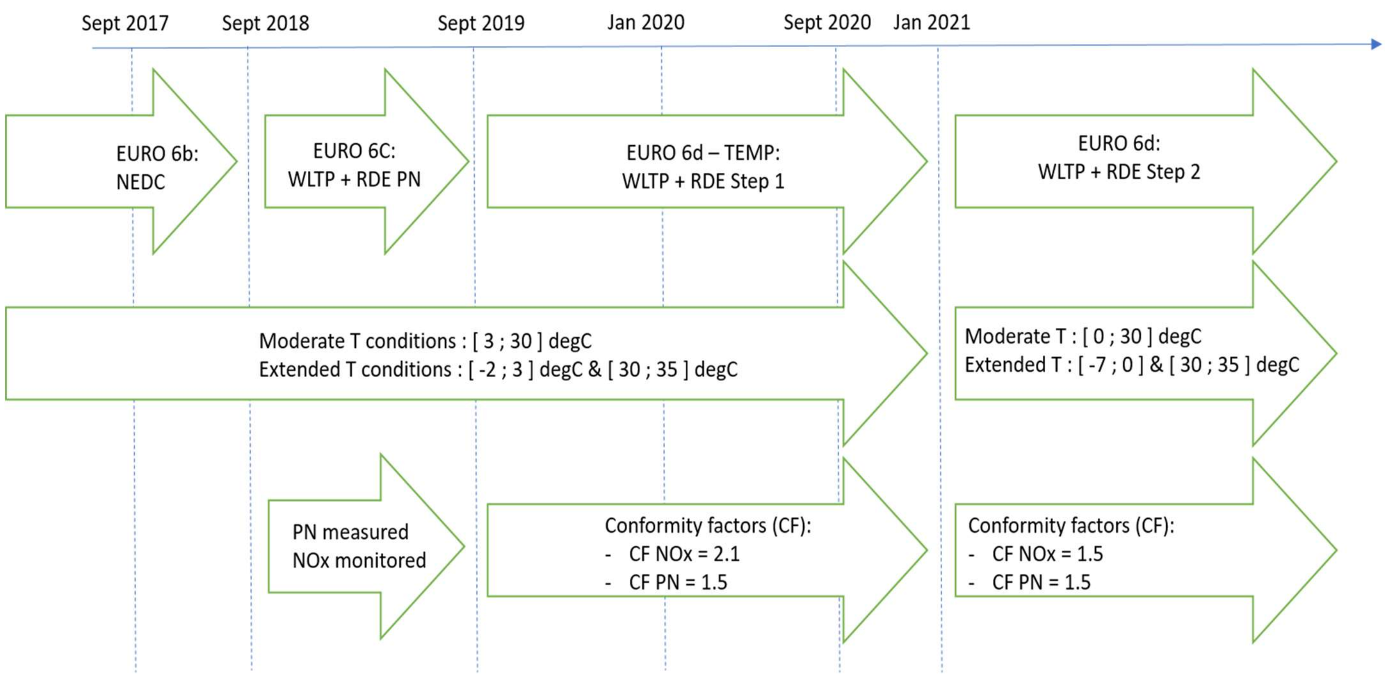


Figure 9 - Regulation - RDE Roadmap - New types

Regulation fixed limits for PN (particle number) and NOx for both gasoline and diesel engine. Regarding diesel engine, which is the one I took in exam, research is more focused in NOx emissions because its's the most severe limit: diesel engine, in fact, produces soot particles which are bigger but less several than gasoline engine: this leads to produce high quantity as particle mass (PM) but less soot particle numbers (PN) which are limited by regulation.
Because of the great effort required to car manufacturer to satisfy emission limits with these new approval cycle, some actions were done to soften the impact of change
First of all it was introduced a time difference between new types and new vehicles: new types, in fact have to respect pollutant limits one or two years before new vehicles.
This temporal difference influenced car manufacturer to homologate new engines before September 2017 to be allowed to install them in new cars until September 2019 even if they are not RDE compliant.
Secondly, two different RDE steps were introduced to let, for the first period, higher NOx emission (conformity factor passes from 2.1 to 1.5).
Finally temperature conditions will become more severe in next years too.
Another important consideration is that this regulation is under development: now RDE pack 3 is valid but it will be replaced by RDE pack 4 in the future: this will cause changes in particular about data evaluation: since pack 3, in fact, NOx emissions have been evaluated using MAW (Moving Average Window) method, a statistical process applied to calculate pollutant emission in g/km based on CO_2 reference values; with pack 4 MAW method will be replaced by calculation of corrected raw emissions (total mass of pollutant (g) divided by total traveled distance (km)).

PEMS Description

During an RDE test, emissions are measured by PEMS (Portable Emission Measurement System) fixed to the vehicle.
PEMS is a compact equipment composed of a gas analyzer module to determine the concentration of pollutants in the exhaust gas on road, a power exchange unit which is connected to batteries placed in the bonnet of the car to give it energy during the trip, a central control unit and a Pitot tube flow meter module that controls Pitot tube connected with the exhaust line to measure the exhaust mass flow.
According the regulation, in fact, PEMS energy must be supplied from an external source and not from vehicle engine and it has to be mounted in order to minimize his effects in car emissions, performance, mass and aerodynamics.
This entire structure is hidden by a cover and connected to the car through a trailer hitch.
This box is connected with a weather station placed on the top of the car and with an operational computer used by the tester to read data during the test.

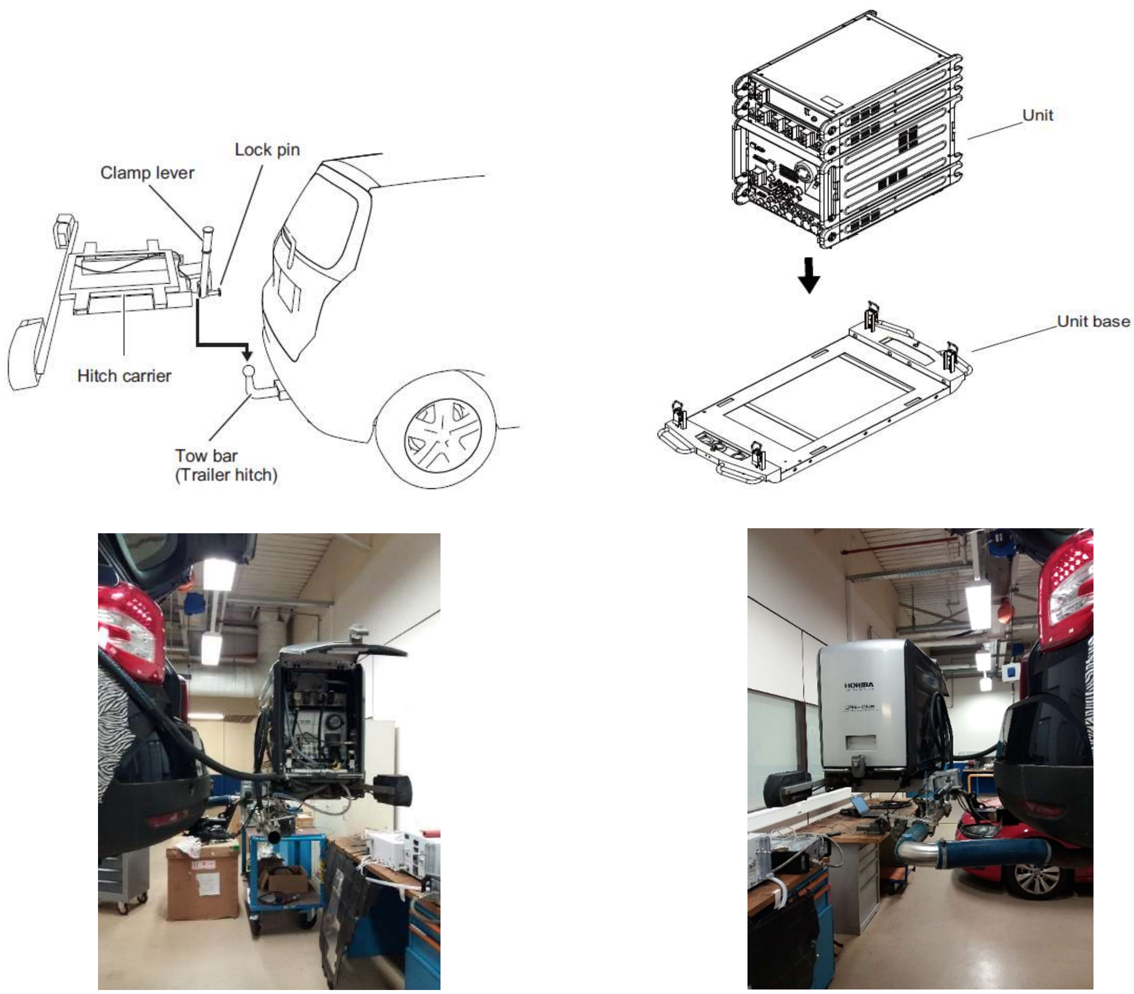


Figure 10 - Regulation - PEMS structure: Horiba PEMS

Test procedure

The procedure that shall be followed before, during and after an RDE tests consists in a series of operations which are highly dependent on PEMS manufacturers.
In this chapter I present operations required by "Horiba" PEMS which was rented in Delphi during my work period.

First of all, after the first mounting of a new PEMS, some checks shall be done:

- Leak check: analysis of PEMS leaks to understand if it has been mounted well;
- Analyzer Performance Check: analysis to verify accuracy, repeatability and PEMS noise for each analyzer: PEMS analyzer shall be plugged into two cylinders which contains a zero gas (N_2) and a span gas (with defined pollutant concentrations) and each pollutant concentration shall be measured for ten times: analyzer performance check passed if accuracy (difference between average measured value and true value), repeatability (difference between each different measurements with the same condition) and noise values are inside limits defined by regulation;
- WLTC test in WindTunnel measuring emission with PEMS and with WLTC bag to make a correlation between them and understand PEMS measurement quality.

Secondly, before and after each RDE test, some others operations and checks shall be done:

- The PEMS shall be switched on, warmed up and stabilized: for "Horiba" PEMS the stabilization shall last at least one hour;
- Purge of gas analyzers plugging the N_2 cylinders to the PEMS to start the gas flowing inside;
- Gas analyzers and Flow Meter calibration to be done before an RDE test: the same cylinders defined previously are plugged to the PEMS to measure CO, CO_2, NO and NO_x emissions to compare them to the expected values (distinctive of the cylinders): if they are different, a correction is applied to the analyzers. Calibration is valid if this difference is inside defined limits, otherwise it shall be repeated;
- Check GPS correct working;
- Drift check to be done after an RDE test: cylinders are plugged to measure emissions to compare obtained values with the results achieved before the start of RDE trip to define gas analyzers drift during the test; if the difference between the two measurements is inside the limits for each emission gas analyzer, measures are reliable. Otherwise the reliability of pollutant emissions measured during the test is not ensured.

Matlab routine for trip validation and evaluation of NOx emissions

Introduction

The introduction of the RDE regulation forces each company to find a reliable process to understand if a particular driving cycle is or is not a valid RDE test and to determine its NOx emissions.
These questions have not an immediate answer because regulation establishes a long list of parameters that have to be identified and compared with the imposed limits in order to define the validity of a test and the quantity of NOx emitted.

The common action plan is to postprocess data in two different ways:

- Using the software placed in the PC provided by the company which leased the PEMS (in our case Horiba);
- Using "Emroad", a free software provided by JRC, the Joint Research Center of the European Commission;

The first software allows to investigate both the two questions we are interested in (trip validity and evaluation of NOx emissions) as the second one is more focused on emission evaluation and it doesn't contain information about all the parameters that have to be checked to validate a test.
In order to be able to perform and analyze an RDE test avoiding the usage of a PEMS (and so, without the PC of the PEMS company) there is the need to create a matlab tool which, receiving all the information by the ECU, is able to establish the validity of the test and to evaluate its NOx emissions.

This work has been divided in two steps:

1. <u>Tool validation</u>: definition of a matlab routine which receives, as input, information from Horiba PEMS in order to compare the results with those obtained by Horiba PC software and Emroad. In this way each of the three software starts from the same information and so, comparing the results, it is possible to validate the Matlab routine;

2. <u>PEMS emulation</u>: development of a matlab routine starting from ECU data and not anymore from PEMS data, in order to be able to perform and analyze an RDE test without renting a PEMS.

Tool validation

In the following pages each part of the matlab routine will be presented explaining the hypothesis which have been made concerning the basis information needed for the calculation and the interpretation of the regulation.
For the sake of clarity the matlab routine description will be divided in: preliminary actions, general requirements, boundary conditions, cumulative positive elevation gain, dynamics requirements, Power Binning method, MAW method, test validity and NOx emissions.
The final product of this matlab routine is a report (.txt file) which contains all necessary information of the specific RDE test.
The Matlab script has been changed to create an interface using "Appdesigner" in order to make it to be usable for every car and every test changing the generical car parameters and the different paths where PEMS file can be taken and where the different images can be saved.
In this way an external user can post-process his own RDE test performed choosing input information required for his vehicle and pressing "Post-processing" button.

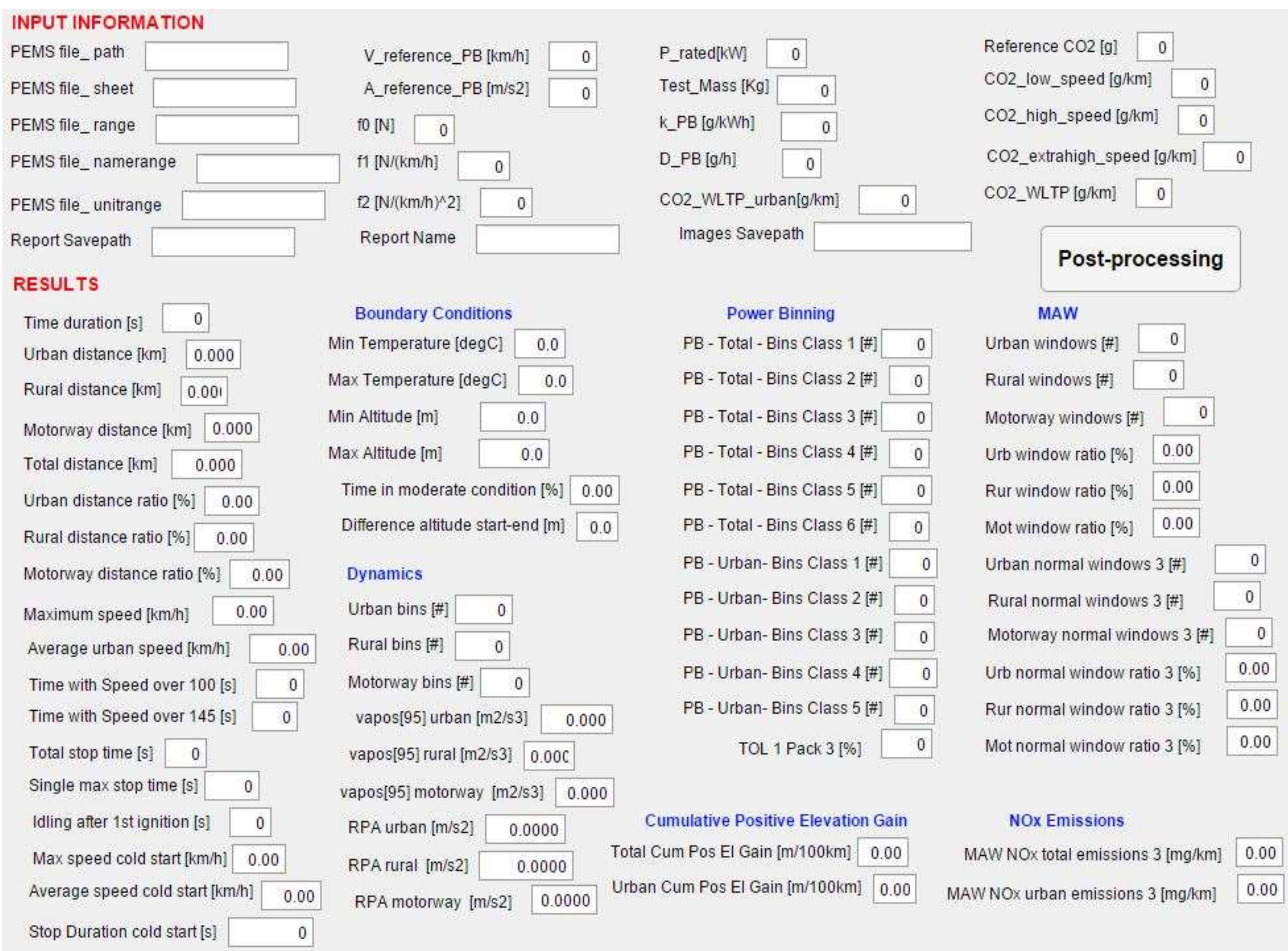


Figure 11 – Matlab routine – Validation tool - App interface

Preliminary actions

The first part of the matlab routine is characterized by three parts:

- Importing & Reading of the PEMS file: to compare Horiba, Emroad and matlab results starting from the same information; it is not imported an excel file containing only measured data but a file which contains some parameters already calculated by Horiba software (such as the exhaust mass flow in g/s which is a parameter that Emroad wants as input);

- List of all the parameters needed to post-process data in order to make them easily exchangeable if a new vehicle has been tested;

- Creation & Opening of a report file: as it has been said before the final goal of this routine is produce a .txt file which contains and checks all the parameters imposed by the regulation. In the report, if the parameter is inside the regulation limits, it is followed by the symbol ‘ - ‘, otherwise there is the symbol ‘ * ’.

General requirements

In this section of the program, passed time, covered distance and vehicle speed are evaluated for each part of the trip (urban, rural and motorway) and for particular conditions (vehicle speed lower than 1 km/h, higher than 100 and 145 km/h, cold start) in order to check the validity of the following parameters:

- Time duration: calculated as a difference between the initial and the final relative time: it shall be comprised between 90 and 120 minutes;
- Urban, rural and motorway absolute distance and their ratio with the total distance: calculated in a 'for cycle' where time and distance of each part are increased according vehicle speed regulation conditions (speed threshold at 60 and 90 km/h): for each part the absolute value shall be higher than 16 km and the ratio shall be more than 15% ;
- Maximum vehicle speed: it shall be comprised between 110 and 160 km/h;
- Average urban speed: ratio between covered distance and passed time in the urban part of the trip (vehicle speed < 60 km/h): it shall be comprised between 15 and 40 km/h;
- Time over 100 km/h: calculated in the same 'for cycle' than urban, rural and motorway distance increasing time according the vehicle speed condition: it shall be bigger than 300 seconds;
- Time over 145 km/h: calculated in the same way as before: it shall be less than 3% of motorway time;
- Total and longest stop time: calculated considering stop as a period with vehicle speed minor than 1 km/h: it shall be comprised between 6 and 30% of urban time as the longest period shall be less than 300 seconds;
- Idling time after first ignition: calculated as the time passed between engine speed bigger than 1 rpm (first ignition) and first instant with engine speed bigger than 1000 rpm (end of idling time): it shall be minor than 15 seconds;
- Cold start maximum and average speed and stop time: first of all cold start duration is defined (maximum duration of 300 seconds but it can last less if the engine reaches a coolant temperature of 70 degC before this period) and then all the parameters are evaluated: they shall respectively be minor than 60 km/h, comprised between 15 and 40 km/h and minor than 90 seconds.

The results are presented in two ways:

a. Table with the absolute values of each parameters obtained by Horiba software, Emroad and the Matlab tool and percentage errors for one test (ID 57);
b. Tables with percentage errors of each parameter calculated for 5 different tests driven with two different cars: Honda Civic T113 (ID 56, 57, 58) and SYG 108 (ID 63, 64).

ID 57						
Parameter	**Unit**	**Horiba**	**Emroad**	**Matlab**	**Error % (Horiba Matlab)**	**Error % (Emroad Matlab)**
Time duration	s	6930	6921	6929	0.01	0.12
Urban distance	km	33.100	33.134	33.134	0.10	0.00
Rural distance	km	28.600	28.631	28.631	0.11	0.00
Motorway distance	km	41.500	41.206	41.482	0.04	0.67
Total distance	km	103.200	102.971	103.247	0.05	0.27
Urban dist. ratio	%	32.07	32.18	32.09	0.06	0.27
Rural dist. ratio	%	27.71	27.80	27.73	0.06	0.27
Motorway dist. ratio	%	40.21	40.02	40.18	0.09	0.40
Maximum speed	km/h	133.80	Not given	133.77	0.02	/
Average urban speed	km/h	28.10	28.10	28.11	0.04	0.04
Time over 100 km/h	s	1165	1167	1165	0.00	0.17
Time over 145 km/h	s	0	0	0	0.00	0.00
Total stop time	s	525	525	525	0.00	0.00
Longest stop time	s	115	Not given	115	0.00	/
Idling after 1st ignition	s	3	Not given	2	33.33	/
Max speed cold start	km/h	45.55	Not given	45.55	0.00	/
Average speed cold start	km/h	24.70	Not given	24.68	0.08	/
Stop time cold start	s	27	Not given	27	0.00	/

EMROAD – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Time duration	0.12	0.12	0.12	0.20	0.13	0.14
Urban distance	0.00	0.00	0.00	0.33	0.29	0.12
Rural distance	0.00	0.00	0.00	0.00	0.14	0.03
Motorway distance	0.65	0.67	0.78	0.00	0.00	0.42
Total distance	0.24	0.27	0.27	0.12	0.14	0.21
Urban dist. ratio	0.24	0.27	0.27	0.19	0.14	0.22
Rural dist. ratio	0.24	0.27	0.27	0.11	0.01	0.18
Motorway dist. ratio	0.40	0.40	0.50	0.11	0.14	0.31
Average urban speed	0.03	0.04	0.03	0.11	0.13	0.07
Time over 100 km/h	0.48	0.17	0.98	0.13	0.00	0.35
Time over 145 km/h	0.00	0.00	0.00	0.00	0.00	0.00
Total stop time	0.00	0.00	0.00	0.00	0.00	0.00

HORIBA – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Time duration	0.01	0.01	0.02	0.02	0.02	0.02
Urban distance	0.07	0.10	0.00	0.14	0.06	0.08
Rural distance	0.13	0.11	0.02	0.19	0.14	0.12
Motorway distance	0.08	0.04	0.14	0.12	0.11	0.10
Total distance	0.04	0.05	0.05	0.05	0.01	0.04
Urban dist. ratio	0.11	0.06	0.04	0.08	0.14	0.09
Rural dist. ratio	0.09	0.06	0.07	0.06	0.15	0.09
Motorway dist. ratio	0.04	0.09	0.10	0.14	0.02	0.08
Maximum speed	0.00	0.02	0.00	0.02	0.00	0.01
Average urban speed	0.19	0.04	0.00	0.07	0.09	0.08
Time over 100 km/h	0.00	0.00	0.00	0.00	0.00	0.00
Time over 145 km/h	0.00	0.00	0.00	0.00	0.00	0.00
Total stop time	0.00	0.00	0.00	0.00	0.00	0.00
Longest stop time	0.00	0.00	0.00	0.00	0.00	0.00
Idling after 1st ignition	25.00	33.33	25.00	57.14	80.00	44.10
Max speed cold start	0.00	0.00	0.00	0.00	0.00	0.00
Average speed cold start	0.07	0.08	0.00	0.33	0.03	0.10
Stop time cold start	0.00	0.00	0.00	4.00	0.00	0.80

Table 8 - Matlab routine - Validation tool - General Requirements - Results and % Errors

The difference between the parameter calculated by Matlab and by the two different software are negligible and due to different approximations.
The only value with an high percentage error is the idling time after 1st ignition even if the absolute error is only of few seconds: this is probably due to different idling concept between matlab tool (idling ends when engine speed = 1000 rpm) and Horiba software (read the code of this program is not allowed and so this condition can not be detected).

Boundary Conditions

A RDE test, differently from NEDC and WLTC, is performed in reality and for this reason it is influenced by a great variability in boundary conditions.
The regulation, in particular checks altitude and ambient temperature: these different parameters influenced two aspects of an RDE test: trip validity and evaluation of pollutant emissions:

- To validate a test the difference between the starting and the final altitude shall be smaller than 100 m (in the matlab tool, the altitude is measured by the GPS and the difference is computed between the first and the last acquired point) and altitude and temperature values shall be inside the interval of moderate or extended conditions defined by regulation;

- To evaluate pollutant emissions the regulation establishes that, for each point in extreme condition, its emission values shall be divided for 1.6.

ID 57						
Parameter	**Unit**	**Horiba**	**Emroad**	**Matlab**	**Error % (Horiba Matlab)**	**Error % (Emroad Matlab)**
Difference altitude (start – end)	m	1.5	4	1.5	0.0	62.50
Minimum Temperature	degC	10.15	Not given	10.05	0.99	/
Maximum Temperature	degC	20.35	Not given	20.25	0.49	/
Minimum Altitude	m	274.0	Not given	274.0	0.00	/
Maximum Altitude	m	410.0	Not given	410.0	0.00	/

EMROAD – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Difference altitude (start – end)	44.44	62.50	85.00	11.72	2.46	41.22

HORIBA – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Difference altitude (start – end)	0.00	0.00	0.00	0.00	0.00	0.00
Minimum Temperature	0.47	0.99	0.92	1.18	0.44	0.80
Maximum Temperature	0.40	0.49	0.05	0.23	0.05	0.25
Minimum Altitude	0.00	0.00	0.00	0.00	0.00	0.00
Maximum Altitude	0.00	0.00	0.00	0.00	0.00	0.00

Table 9 - Matlab routine - Validation tool – Boundary conditions - Results and % Errors

The differences presented between Emroad and the Matlab tool are probably caused by errors in Emroad which does not consider the first and the last line in the proper way: this can be the only reason which can explain this error because all the software start from the same GPS Altitude vector and they only calculate the difference between the starting and final point.
The differences in temperature between Horiba and Matlab, instead, are caused by different approximations and conversion between degC and K.

Cumulative Positive Elevation Gain

The cumulative positive elevation gain is calculated in order to avoid tests with too big road gradients: regulation, in fact, establishes that this parameter calculated for the total trip and for the only urban part shall be smaller than 1200 m for 100 km driven.
To obtain a final value a short procedure has to be followed:

- Calculation of the total distance driven and definition of a discrete distance (starting and finishing with the same values of the total real distance but with an increase of 1 m);
- Calculation of a corrected altitude (h corr) to avoid instant peaks which are not realistic;
- Interpolation of the altitude in the discrete distance;
- Smoothing the first time these values calculating the first road grade (derivative based on the discrete distance) and using it to obtain a different value of altitude;
- Calculation of the second road grade starting from the value of altitude just obtained;
- Computation of the sum of only the positive road grades and division for the total distance driven.

ID 57						
Parameter	**Unit**	**Horiba**	**Emroad**	**Matlab**	**Error % (Horiba Matlab)**	**Error % (Emroad Matlab)**
TOTAL Cumulative Positive Elevation Gain	m/100km	648.7	845.03	648.9	0.03	23.21

EMROAD – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
TOTAL Cumulative Positive Elevation Gain	23.24	23.21	24.72	25.03	24.94	24.23

HORIBA – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
TOTAL Cumulative Positive Elevation Gain	0.03	0.03	0.05	0.03	0.05	0.04

Table 10 - Matlab routine - Validation tool – CPEG – Total - Results and % Errors

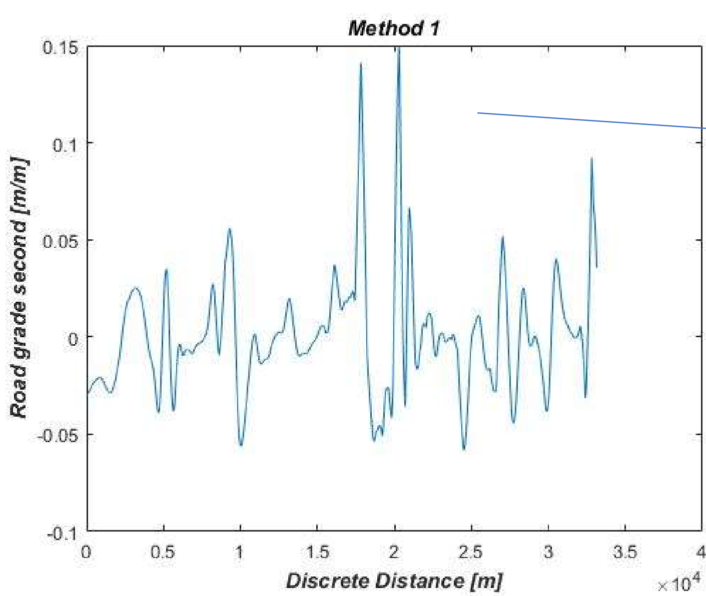
The results obtained by Horiba software and Matlab tool are the same as Emroad results have a quite constant percentage error of 24% probably due to different calculation implemented.

The calculation of the cumulative positive elevation gain for the only urban part is more complex because regulation is not so cleared in this regard.
In an official document of JRC ('QA RDE vs2b.pdf') it is written that the urban cumulative positive elevation gain shall be calculated as the total with only one previous step: delete from the original time series the data corresponding to rural and motorway parts of the trip.
This process, according to me, has no meaning because it causes an overvaluation of the elevation gain: in fact, eliminating all the rural point comprised between two different urban parts, the last point of the first urban part becomes close to the first point of the second urban part and so a gain is calculated between these two points that, in reality, are not close: it is calculated an instantaneous altitude difference which is not real.
It can be compared only Horiba and Matlab results because the calculation of urban positive elevation gain has not been implemented in the last Emroad version yet (EMROAD 5.96 B2).

ID 57				
Parameter	**Unit**	**Horiba**	**Matlab**	**Error % (Horiba Matlab)**
Urban Cumulative Positive Elevation Gain: METHOD 1	m/100km	674.4	1077.4	59.76

HORIBA – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Urban Cumulative Positive Elevation Gain: METHOD 1	48.18	59.76	49.30	65.45	37.97	52.13

Table 11 - Matlab routine - Validation tool – CPEG Urban - Method 1 - Results and % Errors



Peaks caused by the overvaluation of the road grade in urban part deleting rural and motorway parts at the beginning of the calculation.

Figure 12 – Matlab routine - Validation tool – CPEG – Urban - Second road grade - Method 1

For this reason, in the matlab tool, it has been used a different approach based on the discretization of the vehicle speed for each meter driven to take into account, in the second road grades calculated before, only the values which correspond to discrete vehicle speed smaller than 60 km/h (all the second road grades which corresponds to vehicle speed higher than 60 km/h have been set to zero).

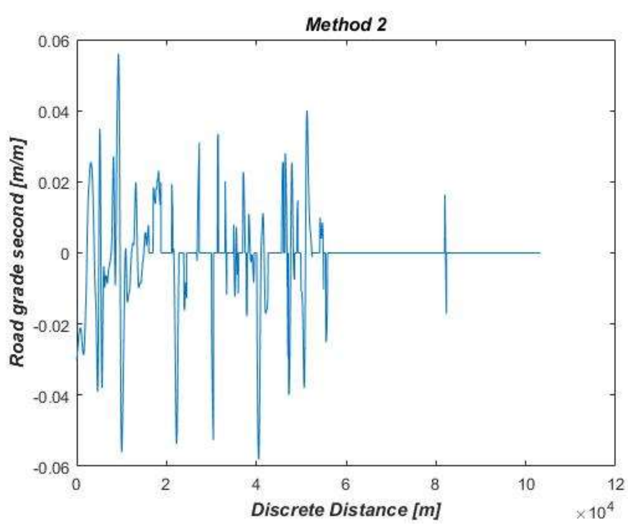
The main difference of the two approaches is that in the method 1 all rural and motorway points are excluded at the beginning of the calculation as in the method 2 they are excluded at the end of the process.
The following results show that this second approach is the same used by Horiba software.

ID 57				
Parameter	**Unit**	**Horiba**	**Matlab**	**Error % (Horiba Matlab)**
Urban Cumulative Positive Elevation Gain: METHOD 2	m/100km	674.4	674.3	0.01

HORIBA – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Urban Cumulative Positive Elevation Gain: METHOD 2	0.08	0.01	0.03	0.01	0.06	0.04

Table 12 - Matlab routine - Validation tool – CPEG Urban - Method 2 - Results and % Errors

For all these reasons the ‘method 2’ has been chosen pending new clarifications of the regulation.



Second road grade without the same peaks as method 1.

Figure 13 – Matlab routine - Validation tool – CPEG – Urban - Second road grade - Method 2

Dynamics requirements: v*a pos [95] & RPA

Dynamics requirements have been set by the regulation in order to avoid tests with too much or not sufficient accelerations.
Three parameters have to be calculated:

- The number of urban, rural and motorway points (bins) characterized by an acceleration higher than 0.1 m/s^2 : the acceleration of each point is calculated as the ratio between the difference of the vehicle speed of the points immediately after and before the one considered and the interval of time (2 seconds because the sampling frequency is 1 Hz). For each of the three parts the number of points shall be higher than 150;
- v*a pos [95]: starting from the points defined before, the product between vehicle speed and vehicle acceleration shall be computed and this class of number shall be sorted in order to find the 95^{th} percentile: if it is not present an interpolation by the two values immediately before and after the 95% shall be done. The three values of urban, rural and motorway shall be minor than reference values which depends on the average speed in the three portion of the RDE test (see the 1^{st} chapter);
- RPA: starting from the values of v*a pos [95] for each point, RPA can be computed for urban, rural and motorway parts: they shall be higher than reference values which are different from v*a pos [95] process but they always depends on the average vehicle speed in each part (see the 1^{st} chapter).

ID 57						
Parameter	**Unit**	**Horiba**	**Emroad**	**Matlab**	**Error % (Horiba Matlab)**	**Error % (Emroad Matlab)**
Number of urban bins	-	1597	Not given	1594	0.00	/
Number of rural bins	-	534	Not given	534	0.00	/
Number of motorway bins	-	477	Not given	477	0.00	/
v*a pos [95] urban	m^2/s^3	11.200	11.174	11.168	0.29	0.05
v*a pos [95] rural	m^2/s^3	15.300	15.269	15.263	0.24	0.04
v*a pos [95] motorway	m^2/s^3	27.100	27.131	27.131	0.11	0.00
RPA urban	m/s^2	0.1920	0.1920	0.1920	0.00	0.00
RPA rural	m/s^2	0.1385	0.1385	0.1385	0.00	0.00
RPA motorway	m/s^2	0.1306	0.1315	0.1306	0.00	0.68

EMROAD – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
v*a pos [95] urban	0.01	0.05	0.01	0.19	0.02	0.06
v*a pos [95] rural	0.03	0.04	0.05	0.02	0.02	0.03
v*a pos [95] motorway	0.05	0.00	0.21	0.02	0.11	0.08
RPA urban	0.00	0.00	0.00	0.15	0.51	0.13
RPA rural	0.00	0.00	0.00	0.00	0.14	0.03
RPA motorway	0.73	0.68	0.33	0.00	0.00	0.35

HORIBA – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Number of urban bins	0.00	0.00	0.00	0.00	0.00	0.00
Number of rural bins	0.00	0.00	0.00	0.00	0.00	0.00
Number of motorway bins	0.00	0.00	0.00	0.00	0.00	0.00
v*a pos [95] urban	0.47	0.29	0.41	0.20	0.17	0.31
v*a pos [95] rural	0.11	0.24	0.08	0.03	0.25	0.14
v*a pos [95] motorway	0.04	0.11	0.19	0.19	0.21	0.15
RPA urban	0.00	0.00	0.00	0.00	0.00	0.00
RPA rural	0.00	0.00	0.00	0.00	0.00	0.00
RPA motorway	0.00	0.00	0.00	0.00	0.00	0.00

Table 13 - Matlab routine - Validation tool – Dynamics Requirements - Results and % Errors

The small differences in the results are only caused by different approximations between the three software.

Power Binning Method

Power Binning Method is present in the RDE regulation in Pack 3 in order to check if, during a test, the entire available power of the vehicle is used: at least five bins shall be inside each power class (the first 6 classes in the total trip and the first 5 classes in the urban part).
In the application of this method in the matlab tool two different approaches have been applied:

- The first approach starts from a file which contains information about time and vehicle speed (used to define the instantaneous acceleration and wheel power for each point) and about CO_2 emissions during a WLTC ran with the same vehicle of the RDE test: these data have been used to obtain k and D (slope and intercept of the specific vehicle veline); then these two parameters have been considered to calculate the instantaneous wheel power for each point of the RDE test starting from CO_2 measurement;
- The second approach starts directly from k and D obtained by Horiba PC based on the CO_2 emitted for each WLTC phase and uses these parameters to calculate the instant wheel power.

The second approach is preferable because it lets the two software (Horiba and Matlab) to start from the same data and understand if the Power Binning method have been applied correctly.
I thinks that the second approach this is better than the first approach because k and D are constant for a vehicle and so it is sufficient to calculate them one time and input them into the matlab tool as constant values for the other tests.
In this analysis only a comparison with Horiba software is presented because Emroad doesn't compute this process: this is probably due to the absence of Power Binning method in the future RDE legislation (RDE pack 4).

First approach

It can be applied only for Honda T 113 because only for these cars all the WLTC information were available. For the SYG, and for all the other cars that have been rented, only the information about the grams of CO_2 emitted for each phase were available and so, only the second approach could be followed.

ID 57				
Parameter	**Unit**	**Horiba**	**Matlab**	**Error % (Horiba Matlab)**
k	g/kWh	655.49	680.09	3.75
D	g/h	1811.28	1758.20	2.93
Total bins Class 1	-	1247	1220	2.17
Total bins Class 2	-	1384	1405	1.52
Total bins Class 3	-	2716	2776	2.21
Total bins Class 4	-	1093	1091	0.18
Total bins Class 5	-	384	336	12.50
Total bins Class 6	-	72	66	8.33

Parameter	Unit	Horiba	Matlab	Error % (Horiba Matlab)
Urban bins Class 1	-	876	859	1.94
Urban bins Class 2	-	1240	1255	1.21
Urban bins Class 3	-	1859	1902	2.31
Urban bins Class 4	-	248	213	14.11
Urban bins Class 5	-	29	16	44.83

Table 14 - Matlab routine - Validation tool – PB – I Approach - Results and % Errors

It is noticed that an error in k and D propagates in the determination of the number of points of the RDE test for each power class: in particular this percentage error increases when the number of bins decreases because a small difference in number causes a big difference in percentage. For this reason this first approach can not be used to understand if the Power Binning method has been applied correctly but we have to define a second approach starting from values of k and D equal for both the software.

Second approach

This approach can be used for Honda T113 and SYG, too: k and D have been calculated by Horiba software using the CO_2 mass emitted for each WLTC phase and they have been taken as an input of the matlab tool.

ID 57				
Parameter	**Unit**	**Horiba**	**Matlab**	**Error % (Horiba Matlab)**
k	g/kWh	655.49	655.49	0
D	g/h	1811.28	1811.28	0
Total bins Class 1	-	1247	1246	0.08
Total bins Class 2	-	1384	1383	0.07
Total bins Class 3	-	2716	2715	0.04
Total bins Class 4	-	1093	1092	0.09
Total bins Class 5	-	384	383	0.26
Total bins Class 6	-	72	71	1.39
Urban bins Class 1	-	876	880	0.46
Urban bins Class 2	-	1240	1238	0.16
Urban bins Class 3	-	1859	1882	1.24
Urban bins Class 4	-	248	226	8.87
Urban bins Class 5	-	29	19	34.48

HORIBA – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Total bins Class 1	0.10	0.08	0.11	3.38	3.46	1.43
Total bins Class 2	0.08	0.07	0.08	1.66	2.51	0.88
Total bins Class 3	0.03	0.04	0.03	0.03	0.07	0.04
Total bins Class 4	0.11	0.09	0.11	0.12	0.12	0.11
Total bins Class 5	0.53	0.26	0.34	0.81	0.96	0.58
Total bins Class 6	2.13	1.39	1.82	100.00	50.00	31.07
Urban bins Class 1	0.13	0.46	0.29	3.24	2.99	1.42
Urban bins Class 2	0.37	0.16	0.09	1.88	2.46	0.99
Urban bins Class 3	0.48	1.24	0.94	1.04	1.01	0.94
Urban bins Class 4	1.33	8.87	2.87	11.64	16.54	8.25
Urban bins Class 5	50.00	34.48	26.32	54.55	66.67	46.40

Table 15 - Matlab routine - Validation tool – PB – II Approach - Results and % Errors

These results are presented as percentage errors even if these value is more related to the absolute number of bins for each power class.
It can be noticed, for example, that the huge difference in percentage error in the total number of bins in class 6 from Honda tests (ID 56, ID 57, ID 58) and SYG tests (ID 63, ID 64) is caused by the fact that the absolute value of bins calculated by Horiba for Honda tests is about 60 as for SYG tests is 1 or 2 (so even if the error is 50 % the relative difference in the number of bins for that class is only 1).
The evaluation of Power Binning method has not been dealt with in depth for two reasons: first of all because only Horiba software compute this method as Emroad does not (and so we can not be sure that Horiba software computes it correctly) and, secondly, because this method will not be used anymore to validate the RDE trip. in the future regulation (RDE pack 4).

MAW method

This method is the central point of the RDE regulation: in the current regulation, in fact, it is used to validate the trip and evaluate NOx emissions but, in contrast to Power Binning method, it will be also present in RDE pack 4, even if only for trip validity.
In the matlab tool two different methods have been implemented to compute the Moving Averaging Windows process, due to two possible interpretations of the regulations.
It is written that data characterized by vehicle ground speed lower than 1 km/h '*shall not be considered for calculation of the CO_2 mass, the emission and the distance of averaging windows*' (COMMISSION REGULATION (EU) 2017-1151 Consolidated): so, it is not cleared if these points shall be considered in the time definition of the window or they shall not.
This is a relevant problem because if these points are counted in the time definition, the average vehicle speed for each window decreases and the distribution of urban, rural and motorway windows changes as the total number of windows remains constant.
In order to understand which one of the two approaches is correct, both of them have been computed and the results have been compared with Horiba and Emroad software.
In the first approach all the points characterized by vehicle speed lower than 1 km/h are excluded in the entire MAW process, and so also in the time definition, as in the second approach they are taken into account in the definition of window time duration.
For this reason, using the second approach, the average vehicle speed for each window decreases and there are more urban and less rural windows than the first approach.

ID 57 – 1st approach						
Parameter	**Unit**	**Horiba**	**Emroad**	**Matlab**	**Error % (Horiba Matlab)**	**Error % (Emroad Matlab)**
Urban windows	-	2434	2149	2147	11.79	0.09
Rural windows	-	2785	2558	2559	8.11	0.04
Motorway windows	-	1440	1426	1427	0.90	0.07
Total number of windows	-	6659	6133	6133	7.90	0.00

ID 57 – 2nd approach						
Parameter	**Unit**	**Horiba**	**Emroad**	**Matlab**	**Error % (Horiba Matlab)**	**Error % (Emroad Matlab)**
Urban windows	-	2434	2149	2652	8.96	23.41
Rural windows	-	2785	2558	2057	26.14	19.59
Motorway windows	-	1440	1426	1425	1.04	0.07
Total number of windows	-	6659	6133	6134	7.88	0.02

HORIBA – MATLAB: % ERROR – 1st approach						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Urban windows	14.66	11.79	12.53	14.84	8.25	12.42
Rural windows	3.28	8.11	8.83	9.29	4.36	6.78
Motorway windows	0.41	0.90	0.24	5.03	0.65	1.45

EMROAD – MATLAB: % ERROR – 1st approach						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Urban windows	0.11	0.09	0.12	0.00	0.00	0.06
Rural windows	0.04	0.04	0.08	0.04	0.00	0.04
Motorway windows	0.21	0.07	0.41	0.29	0.00	0.20

HORIBA – MATLAB: % ERROR – 2nd approach						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Urban windows	10.12	8.96	33.76	15.09	8.30	15.25
Rural windows	21.59	26.14	40.41	29.76	17.09	27.00
Motorway windows	0.62	1.04	0.24	5.68	1.52	1.82

EMROAD – MATLAB: % ERROR – 2nd approach						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Urban windows	28.90	23.41	53.10	25.15	18.05	31.72
Rural windows	18.90	19.59	34.68	22.60	13.31	21.82
Motorway windows	0.00	0.07	0.41	0.39	0.87	0.35

Table 16 - Matlab routine - Validation tool – MAW – I & II Approaches Results

First of all it is noticed that the two different approaches cause different errors in the amount of urban and rural windows as in the number of motorway windows the errors is quite constant: this happens because instants with vehicle speed lower than 1 km/h occur only in the first part of the trip and so they influence the window definition only at the beginning when the average vehicle speed is lower than 80 km/h (speed threshold to define motorway windows).

For this reason to understand which approach is correct, errors in the number of urban and rural windows shall be detected: analyzing the average Emroad – Matlab percentage error is evident that the correct approach is the 1st one (0.06 and 0.04 % against 31.72 and 21.82 % of error).

In this analysis it can be noticed that Horiba software obtains different results: in particular it always overestimates the number of total windows (this is the same for the two different approaches which give the same total amount of window): this mistake happens because Horiba starts a new window even if the instantaneous vehicle speed is lower than 1 km/h.

This is evident because:

total n° of windows computed by Matlab or Emroad + time with vehicle speed lower than 1 km/h

=

total n° of windows computed by Horiba

To validate the matlab tool is sufficient the proximity between Matlab and Emroad results (official software of JRC).
In this way the first approach has been defined as the correct one and its intermediate results can be used to develop completeness and normality checks for each RDE test.
In order to pass the completeness check at least 15 % of the total number of windows shall be urban, rural and motorway.

ID 57						
Parameter	**Unit**	**Horiba**	**Emroad**	**Matlab**	**Error % (Horiba Matlab)**	**Error % (Emroad Matlab)**
Urban windows ratio	%	36.55	35.04	35.01	4.23	0.09
Rural windows ratio	%	41.82	41.71	41.73	0.23	0.04
Motorway windows ratio	%	21.62	23.25	23.27	7.60	0.07

HORIBA – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Urban windows ratio	8.82	4.23	4.63	5.03	3.21	5.18
Rural windows ratio	3.34	0.23	0.61	1.26	0.78	1.24
Motorway windows ratio	6.41	7.60	8.75	6.06	4.86	6.73

EMROAD – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Urban windows ratio	0.14	0.09	0.03	0.00	0.00	0.05
Rural windows ratio	0.00	0.04	0.17	0.06	0.00	0.05
Motorway windows ratio	0.17	0.07	0.32	0.26	0.02	0.17

Table 17 - Matlab routine - Validation tool – MAW– Completeness - Results and % Errors

In order to detect the normality check the number of urban, rural and motorway normal windows shall be calculated: to pass the check at least the 50% of windows shall be normal for each of the three sections of the RDE test.
A window is defined normal if it is inside the green bandwidth (± 25%) in MAW graphic, taking into account that the green up tolerance can be increased until +30% if the normality check doesn’t pass at lower tolerances.
In the following MAW graphics, each point represents a window and it is green if it corresponds to a normal window.
The three graphics produced by the three different software are presented to show the achievement of the same results with the matlab tool.
In addition numerical results are presented to compare the results of this process (amount of normal windows and normality ratio for each RDE test part) using the three different software.

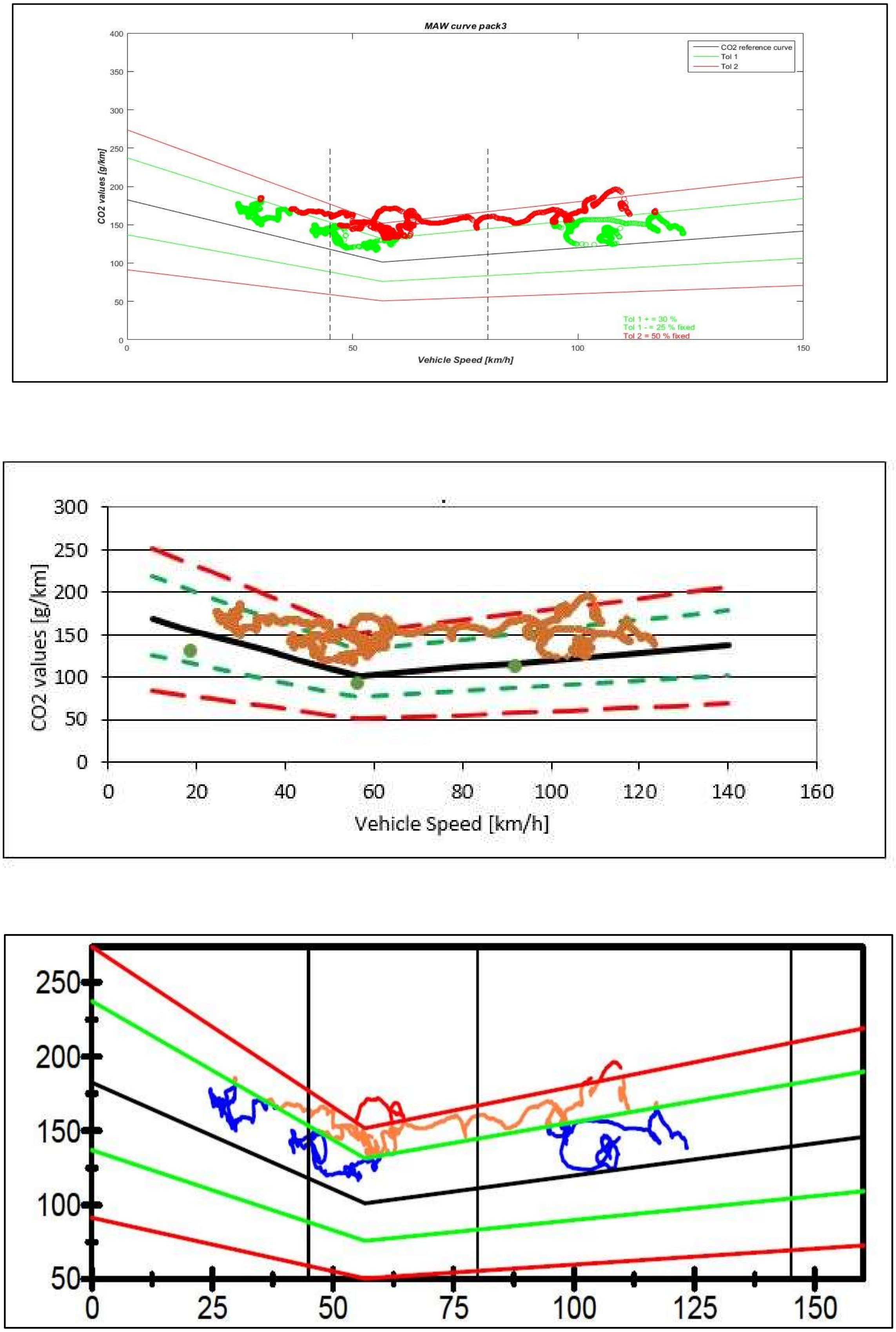


Figure 14 - Matlab routine – Validation tool – MAW – Matlab, Emroad & Horiba – ID 57

ID 57						
Parameter	**Unit**	**Horiba**	**Emroad**	**Matlab**	**Error % (Horiba Matlab)**	**Error % (Emroad Matlab)**
Urban normal windows	-	2133	Not given	1906	10.64	/
Rural normal windows	-	1087	Not given	924	15.00	/
Motorway normal windows	-	944	Not given	933	1.17	/
Urban normal ratio	%	87.63	88.74	88.78	1.30	0.04
Rural normal ratio	%	39.03	36.16	36.11	7.49	0.14
Motorway normal ratio	%	65.56	65.57	65.38	0.26	0.29

HORIBA – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Urban normal windows	16.61	10.64	12.96	14.80	8.25	12.65
Rural normal windows	5.94	15.00	6.12	10.20	4.36	8.33
Motorway normal windows	1.94	1.17	0.43	5.52	0.69	1.95
Urban normal ratio	2.28	1.30	0.50	0.00	0.00	0.82
Rural normal ratio	2.75	7.49	2.98	0.96	0.00	2.84
Motorway normal ratio	1.53	0.26	0.18	0.56	0.01	0.51

EMROAD – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
Urban normal ratio	0.05	0.04	0.02	0.00	0.00	0.02
Rural normal ratio	0.04	0.14	0.45	0.01	0.00	0.13
Motorway normal ratio	0.00	0.29	0.02	0.19	0.00	0.10

Table 18- Matlab routine - Validation tool – MAW– Normality - Results and % Errors

The comparison between the results obtained by Emroad and Matlab lets to validate the tool. Horiba results are different in absolute terms (number of normal windows) because, as it has been shown before, the total number of windows is different but the normality ratio is similar to the results obtained by the other two software.
The proximity of the values obtained by the different software can be noticed by the observation of the MAW graphics: they present the same windows distribution.

Test validity

In order to have a valid RDE test, each of the previous conditions shall be respected: to compute this in the matlab tool, for each different condition it has been assigned a number at the vector 'validity': 1 if the condition is satisfied, otherwise 0.
At the end of the matlab script if, at least, one element of the vector is 0 the test is not valid.

Test	Horiba	Emroad	Matlab
ID 56	YES	YES	YES
ID 57	NO (rural normality)	NO (rural normality)	NO (rural normality)
ID 58	NO (rural normality)	NO (rural normality)	NO (rural normality)
ID 63	NO (power binning)	YES	NO (power binning)
ID 64	NO (power binning)	YES	NO (power binning)

Table 19- Matlab routine - Validation tool – Validity check

As the intermediate results, presented up to now, showed, there is no a big difference in the general evaluation of RDE test validity.
This is due to the small differences between the results of the three software that do not influence the validation of the test.
The only difference is that Emroad doesn't compute the Power Binning method and so ID 63 and ID 64 are valid according this software.
This is not a relevant problem because, as it has been said before, Power Binning method will be eliminated by the future RDE legislation.

NOx emissions

The second important point in a RDE test, after the trip validation, is the NOx emissions evaluation.
In Emroad software and in the Matlab tool this analysis starts importing the vector of the instantaneous NOx emission, calculated by Horiba software, in g/s.
First of all, all the instantaneous emission referred to instant time when extended condition are present (temperature and altitude) shall be divided for 1.6.
Then the regulation establishes that MAW method shall be used to process data and obtain final values of NOx emissions in mg/km for the total trip and the urban part.
According this method a weighting factor shall be applied to each window taking into account its position in MAW graphic:

- 1 if it is inside the green bandwidth;
- From 0 to 1 with a linear variation if it is between green and red lines;
- 0 if it is outside the red bandwidth.

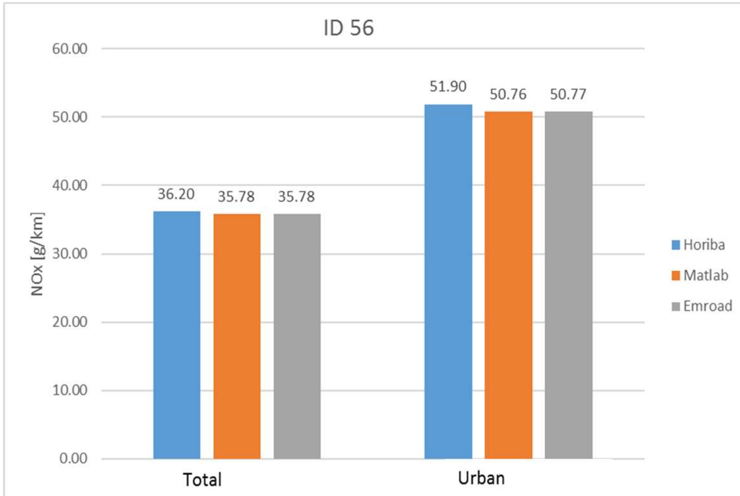
The only exception is that if a window contains cold start points the weighting factor is set to 1 whatever is its position.
At the end a weighting average shall be done.

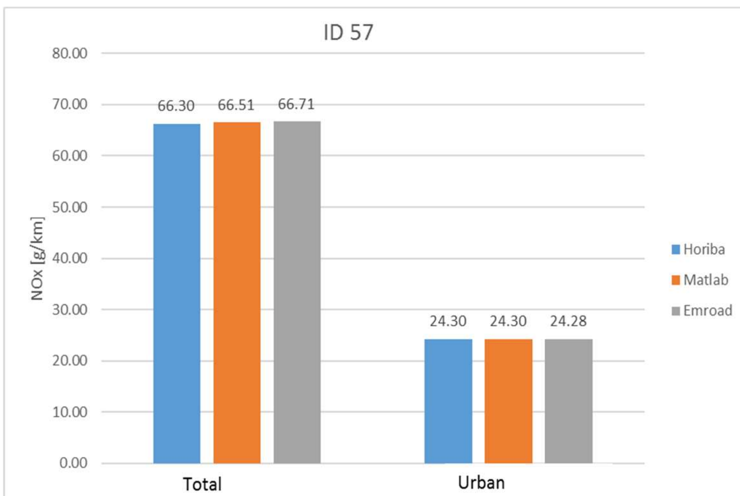
ID 57						
Parameter	**Unit**	**Horiba**	**Emroad**	**Matlab**	**Error % (Horiba Matlab)**	**Error % (Emroad Matlab)**
NOx Total Emissions	mg/km	66.30	66.71	66.51	0.32	0.30
NOx Urban Emissions	mg/km	24.30	24.28	24.30	0.00	0.08

HORIBA – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
NOx Total Emissions	1.16	0.32	0.12	0.05	0.31	0.39
NOx Urban Emissions	2.20	0.00	0.36	1.28	0.45	0.86

EMROAD – MATLAB: % ERROR						
Parameter	**ID 56**	**ID 57**	**ID 58**	**ID 63**	**ID 64**	**Average**
NOx Total Emissions	0.00	0.30	1.36	0.02	12.44	2.82
NOx Urban Emissions	0.02	0.08	0.01	0.01	6.38	1.30

Table 20- Matlab routine - Validation tool – NOx Emissions - Results and % Errors





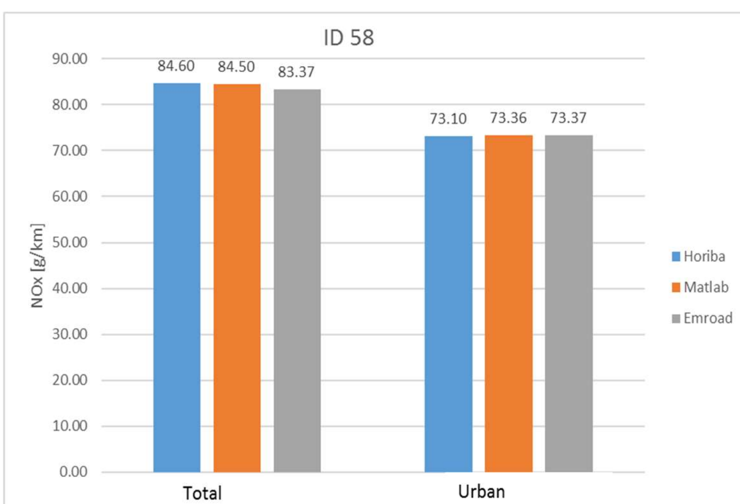


Figure 15 - Matlab routine - Validation tool – NOx - Horiba, Matlab and Emroad comparison

Results of three software are quite similar: the only difference is in ID 64 (histogram not present because it is a SYG test with private information).
This is caused by different extended temperature conditions: in Horiba and Matlab the 2nd step of RDE pack 3 has been applied (extended temperature condition if it belongs to [-7 ; 0] degC) as in Emroad the 1st step has been applied (extended temperature condition if T [-2 ; 3] degC).
This difference occurs only in ID 64 because the lowest temperature is about 2 degC as in the other IDs it is higher than 3 degC.
If the definition of extended conditions is changed in the matlab tool, to be the same of Emroad, the results become similar:

ID 64: EMROAD Version 5.96 B2 – MATLAB: % ERROR (Matlab and Emroad RDE step 1)	
Parameter	**ID 64**
NOx Total Emissions	4.73
NOx Urban Emissions	0.39

Table 21- Matlab routine - Validation tool – NOx emissions – RDE step 1 - % Errors

The percentage error is still high because of different temperature conversion which causes a small difference in the number of points considered as extended by Matlab and Emroad.
In both software the input temperature is in degC but in the Matlab routine isn't applied any conversion as in Emroad the temperature is converted in K (adding 273.15); then the extended condition check is made considering a limit temperature of 276.00 K (and not 276.15 K as it should be): for this reason Emroad considers points between 276.00 and 276.15 K in normal condition as the Matlab tool considers them in extended.
Because of this mistake, Emroad divides less instantaneous NOx emission points for 1.6 and so its final result of NOx emissions is higher than Matlab.
In ID 64 this mistake causes problem only in the total evaluation of NOx emission because temperature is about 3 degC in the rural and motorway part of the trip as in the urban part the temperature is higher.
This problem has been solved in the last version of Emroad released after this analysis (EMROAD 5.96 B3).

ID 64: EMROAD Version 5.96 B3 – MATLAB: % ERROR (Matlab and Emroad RDE step 1)	
Parameter	**ID 64**
NOx Total Emissions	0.00
NOx Urban Emissions	0.02

Table 22 - Matlab routine - Validation tool – NOx emissions – RDE step 1 (New version)

In the tool they are also implemented calculation to define raw emission of CO_2, CO and PN (this last result will be present if a future rented PEMS will contain analyzer to measure PN).

Conclusion

A Matlab routine has been developed to validate the RDE trip and to process the emissions results according to regulation (EC) 2017/1151.
Results obtained by post-processing PEMS data using the developed Matlab routine have been compared with Horiba and EMROAD results and the following consideration can be done:

- ✓ In the general requirements (time, vehicle speed, distance, stop time and cold start parameters), boundary conditions (altitude and temperature) and dynamics requirements (v*a pos [95] & RPA) the results of the three software are in good agreement;
- ✓ In the calculation of urban cumulative positive elevation gain there are two possible approaches: the 2nd one is the right one confirmed by Horiba results;
  EMROAD computes only the total cumulative positive elevation gain but in a wrong way (different results compared to Horiba and Matlab);
- ✓ Power Binning method has been applied correctly (small difference in the absolute number of bins for each power class);
- ✓ MAW method can be processed following two different approaches: the 1st one is the right one confirmed by EMROAD results. Horiba software overestimates the number of total windows due to an error in their interpretation of the regulation;
- ✓ Despites the different errors in Horiba and EMROAD the final results in NOx emissions (total and urban) from the three software are almost equal;
- ✓ The developed Matlab Routine has been successfully validated by comparison with Horiba and EMROAD, and different errors have been identified in the other two software.

PEMS Emulation

The final goal of the matlab routine is to be able to perform and analyze an RDE test without using a PEMS: for this reason, the routine described up to now, after being validated, shall be changed in order to receive as input information data directly from the ECU (recorded by Inca software) and not anymore from the PEMS.
In the next pages the structure of the last chapter is followed explaining which parameters shall be changed to achieve this goal and comparing the new results with the ones obtained postprocessing PEMS data with the previous matlab routine just validated.
Data are compared with the previous Matlab routine and not with Emroad or Horiba software in order to analyze the differences in the results caused only by the different input information.
Three test results are compared: ID 58, ID 61, ID 213.
One of the main problem of this approach is the absence of simultaneous acquisition between the two different software: difference of few seconds in the start and the end of PEMS and Inca acquisition cause small discrepancies between the test post-processed starting by PEMS data and the one post-processed using Inca data.
In order to reduce this phenomena and study its effect in the results, the first two tests (ID 58 and ID 61 which were driven in the previous months for other purposes) are compared with ID 213 in which an higher coincidence in time between PEMS and Inca software has been searched.

Preliminary actions

In this part of the Matlab script, the main difference with the previous routine is the need to read a .dat file and not anymore an excel file because the input information are provided by Inca software and not anymore by the Horiba PEMS.
For this reason two matlab functions shall be used ('*ha_mdfread*' and '*ha_commontimegrid*') with the necessity to define an interpolation frequency (it has been chosen a frequency of 1 Hz in order to have the same sampling frequency as PEMS data).
It is also present the list of all the input information needed by the tool to compute the post-process of the test.
The final product of the Matlab routine is a report which contains all the parameters required to validate the trip and analyze emission results followed by the symbol ' - ' if it is inside the limits defined by regulation otherwise the symbol ' * ' (example in the following page for ID 58).

RDE test REPORT ID 58

GENERAL REQUIREMENTS

```
Time duration =   6522 s  -
Urban distance = 33.032 km  -
Rural distance = 29.025 km  -
Motorway distance = 35.932 km  -
Total distance = 97.990 km
Urban distance ratio = 33.709%  -
Rural distance ratio = 29.621%  -
Motorway distance ratio = 36.670%  -
Maximum speed = 134.31 Km/h  -
Average urban =  30.02 Km/h  -
Time over 100 km/h =    936 s  -
Time over 145 km/h =      0 s  -
Total stop time =    507 s  -
Longest Stop Time =    105 s  -

Idling & Cold Start:
Idling time after first ignition =      4 s  -
Max speed during COLD START = 51.869 Km/h  -
Average speed during COLD START = 32.914 Km/h  -
Stop duration during COLD START =      4 s  -
```

BOUNDARY CONDITIONS

```
Difference altitude start - end =   10.2 m  -
Temperature range =  6.00 - 16.00 degC
Altitude range = 262.3 - 405.0 m
100 % in Moderate Temperature Conditions
```

CUMULATIVE POSITIVE ELEVATION GAIN

```
Total Cumulative positive elevation gain = 663.45 m/100km   -
Urban Cumulative positive elevation gain = 681.30 m/100km   -
```

VAPOS[95] & RPA

```
Urban bins =   1458   -
Rural bins =    483   -
Motorway bins =    406   -
vapos[95] urban = 11.245 m^2/s^3  -
vapos[95] rural = 19.320 m^2/s^3  -
vapos[95] motorway = 22.532 m^2/s^3  -
RPA urban = 0.1799 m/s^2  -
RPA rural = 0.1305 m/s^2  -
RPA motorway = 0.0913 m/s^2  -
```

POWER BINNING

```
Total trip
Power class NO 1 =   1205  -
Power class NO 2 =   1138  -
Power class NO 3 =   2836  -
Power class NO 4 =    974  -
Power class NO 5 =    295  -
Power class NO 6 =     51  -
```

```
Urban part
Power class NO 1 =    842  -
Power class NO 2 =   1019  -
Power class NO 3 =   1821  -
Power class NO 4 =    240  -
Power class NO 5 =     32  -
```

MAW

```
Completeness check
Urban windows  =   1616
Rural windows  =   2628
Motorway windows  =   1264
Urban windows ratio =  29.34 %   -
Rural windows ratio =  47.71 %   -
Motorway windows ratio =  22.95 %   -

Normality check PACK 3
Tol 1 + =     30%
Tol 1 - = 25% fixed
Urban normal windows =   1557
Rural normal windows =    913
Motorway normal windows =   1168
Urban normal windows ratio =  96.35 %   -
Rural normal windows ratio=  34.74 %   *
Motorway normal windows ratio=  92.41 %  -

Normality check PACK 4
Tol 1 Urban + = 45% fixed
Tol 1 Rural & Motorway = 40% fixed
Tol 1 Urban & Rural & Motorway - = 25% fixed
Urban normal windows =   1479
Rural normal windows =    766
Motorway normal windows =   1178
Urban normal windows ratio =  91.52 %   -
Rural normal windows ratio=  29.15 %   *
Motorway normal windows ratio=  93.20 %  -
```

TEST NOT VALID!!

EMISSIONS

```
PACK 3: MAW NOx Emissions:
- Total:  66.11 mg/km
- Urban:  54.23 mg/km

PACK 4:NOx Emissions:
- Total:  60.83 mg/km
- Urban:  23.63 mg/km
```

CO_2 Raw emissions: 134.34 g/km

Figure 16 – Matlab routine – Emulation tool – Preliminary actions - Report - ID 58

As in the previous tool, an interface has been created in order to make the program usable by different users with different input information.

For the sake of clarity two different applications have been created, one for the computation of post-processing according RDE pack 3 and one for the computation of post-processing according RDE pack 4: the differences between them regard some input information, MAW process and NOx emissions results.
The two examples of the generical interfaces have been presented below.

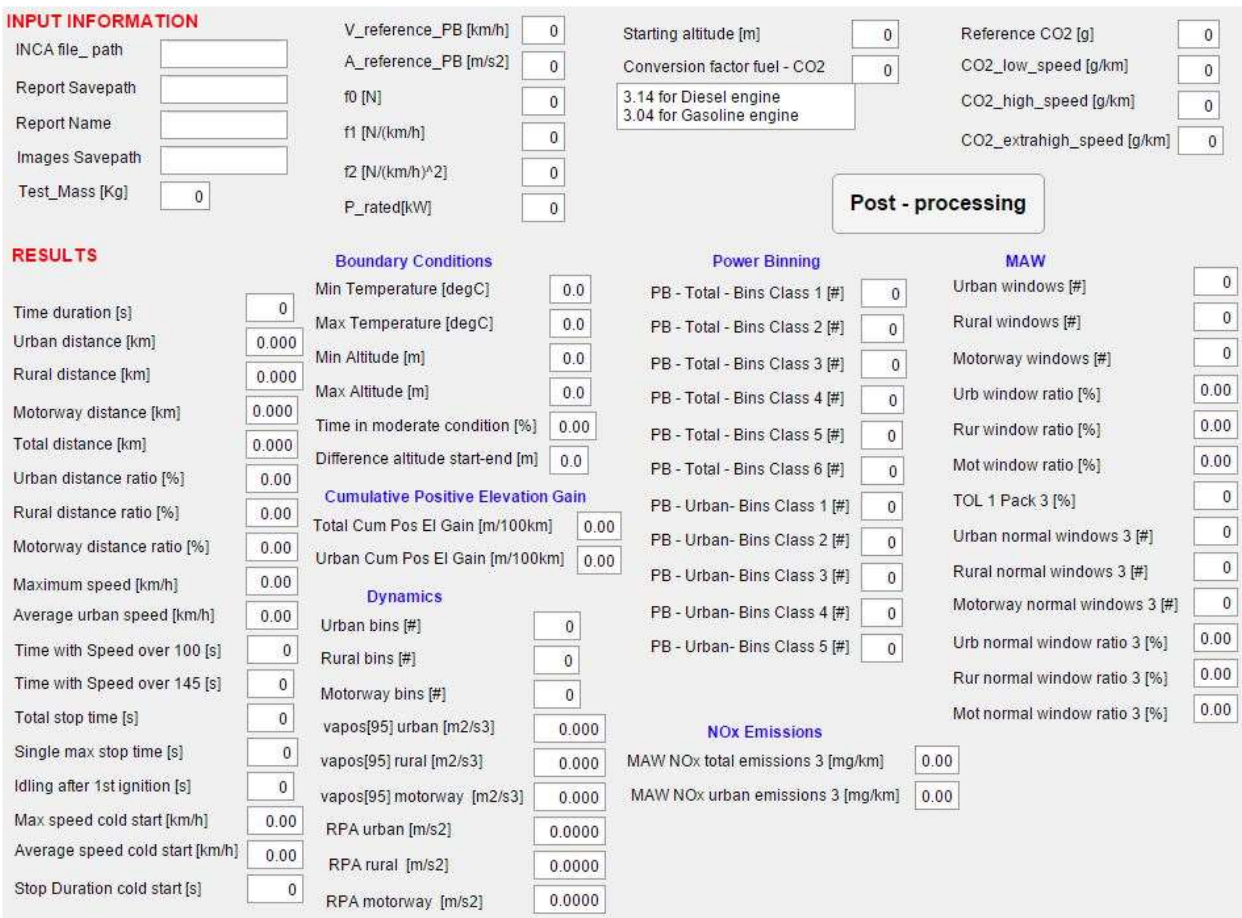


Figure 17 – Matlab routine – Emulation tool – Preliminary actions - Interface - RDE Pack 3

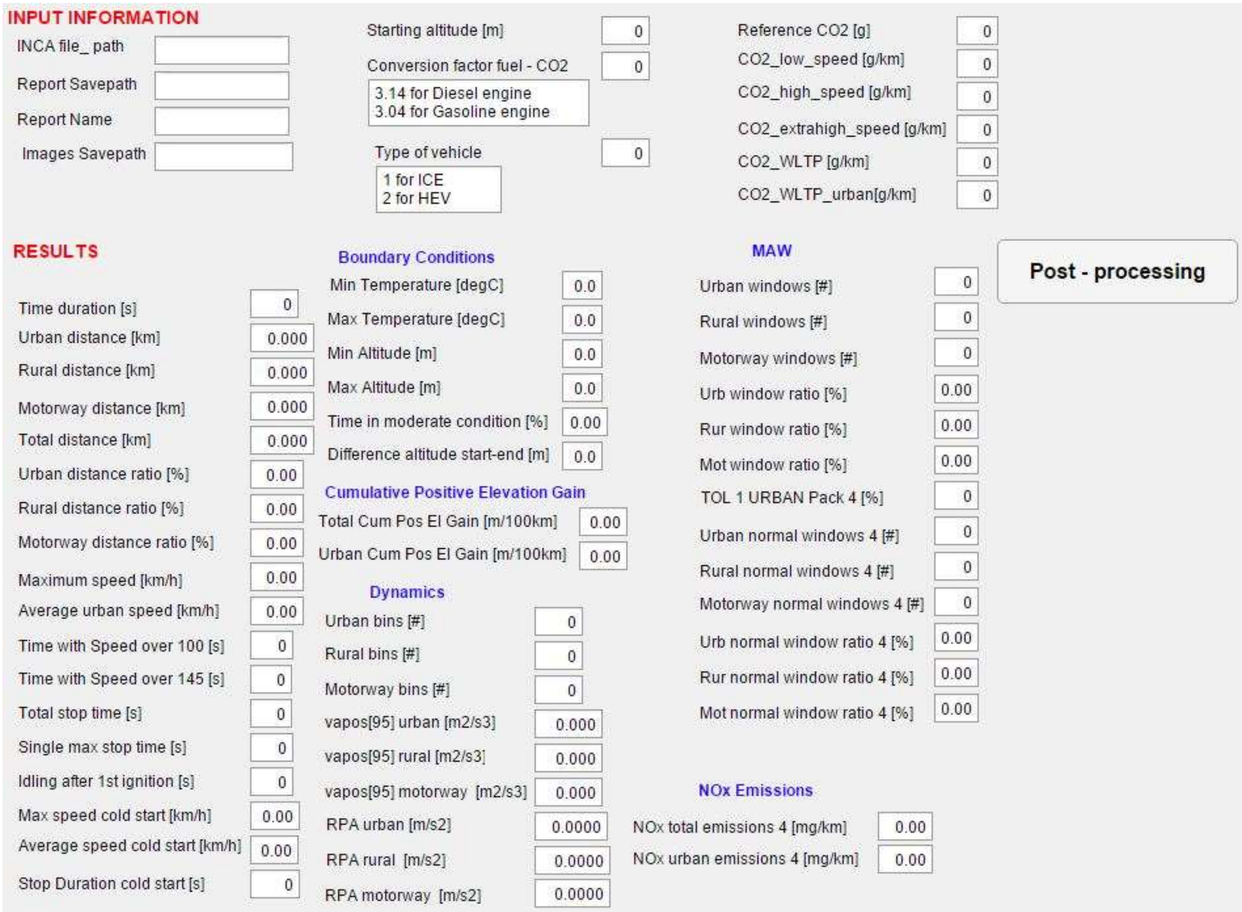


Figure 18 – Matlab routine – Emulation tool – Preliminary actions - Interface - RDE Pack 4

General requirements

Time and vehicle speed information derive from Inca software which communicates directly with ECU and not anymore from the PEMS (which takes information from OBD or GPS). Sensors measure the vehicle speed, the injection speed (used to define the time of the first ignition of the combustion), the engine speed (to define the end time of idling condition) and the coolant temperature (to define the end of the cold start period).
The presence of small percentage errors is caused by different start and end time of the test comparing PEMS and Inca software and by small differences in the vehicle speed detected by GPS (PEMS) and ECU (INCA) in particular at high speed (see the vehicle speed detail in the following picture) which influence all the parameters, in particular regarding the motorway part of the trip.

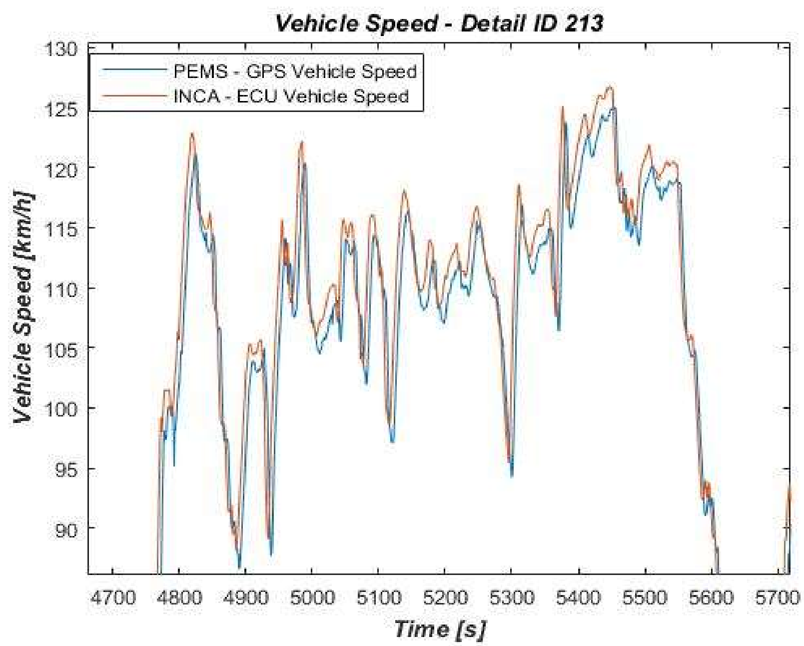


Figure 19 - Matlab routine – Emulation tool – Gen. Req. - GPS & ECU Vehicle Speed

VALIDATION – PEMS EMULATION % ERROR				
Parameter	**ID 58**	**ID 61**	**ID 213**	**Average**
Time duration	0.91	0.15	0.19	**0.42**
Urban distance	0.20	0.97	0.38	**0.52**
Rural distance	0.76	1.29	1.42	**1.16**
Motorway distance	7.41	5.49	3.38	**5.43**
Total distance	2.76	1.75	1.64	**2.05**
Urban dist. ratio	2.89	0.77	1.99	**1.88**
Rural dist. ratio	1.95	2.99	0.22	**1.72**
Motorway dist. ratio	4.53	3.68	1.71	**3.31**
Maximum speed	1.67	1.40	1.33	**1.47**
Average urban speed	0.40	1.36	1.12	**0.96**
Time over 100 km/h	1.08	2.37	4.65	**2.70**
Time over 145 km/h	0.00	0.00	0.00	**0.00**
Total stop time	2.22	0.73	5.45	**2.80**
Longest stop time	0.94	0.00	0.00	**0.31**
Idling after 1st ignition	33.33	0.00	18.52	**17.28**
Max speed cold start	1.60	1.33	1.97	**1.63**
Average speed cold start	1.87	1.72	4.98	**2.86**
Stop time cold start	0.00	0.00	6.25	**2.08**

Table 23 - Matlab routine – Emulation tool – General requirements – % Errors

In this part of the script the graphic vehicle speed versus time is produced in order to show its shape during the RDE trip.
The green and red lines represent the upper limits of the urban (60 km/h) and rural part (90 km/h).

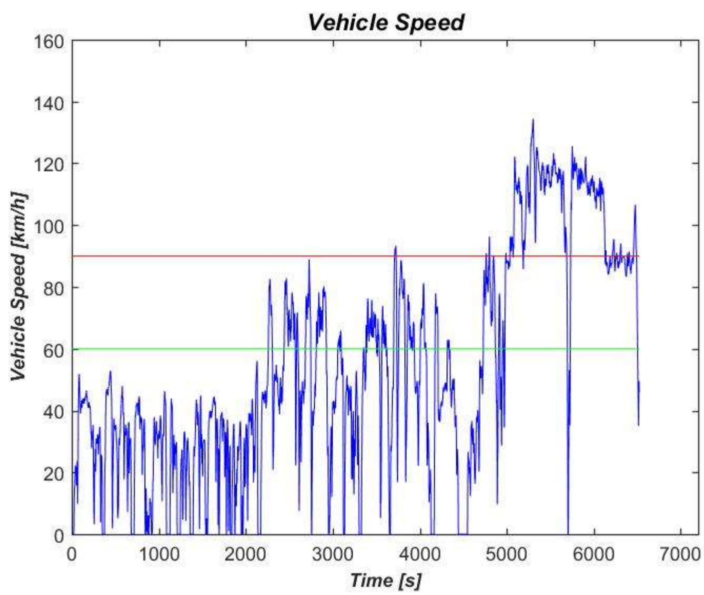


Figure 20 - Matlab routine – Emulation tool – Gen. Req. - ECU Vehicle Speed ID 213

Boundary conditions

In the PEMS equipment temperature information are provided by the weather station: in the new Matlab routine it is replaced by a temperature measurement of the ambient air made by a sensor. The sensor has a smaller resolution than the weather station but for this purpose, which is to define moderate, extended or not valid temperature condition, higher precision is not required.

In order to achieve altitude information there are two possible approaches:

- 1st approach: calculation of altitude from atmospheric pressure and ambient temperature (both measured by sensors) using an experimental formula which is valid between 100 and 2000 m above sea level:

$$h = \frac{\left(\left(\frac{p_0}{p}\right)^{\frac{1}{5.257}} - 1\right) x\ (T + 273.15)}{0.0065}$$

- ✓ P = atmospheric pressure [KPa] ;
- ✓ P_0 = pressure at sea level = calculated by the tool using the inverse of formula and receiving as input by the user the starting trip altitude: this method has been used in order to calibrate data depending on the daily weather (P_0 is not constant equal to 101.325 KPa) [KPa] ;
- ✓ T = ambient temperature [°C]

Source: *https://physics.stackexchange.com/questions/333475/how-to-calculate-altitude-from-current-temperature-and-pressure*

- 2nd approach: usage of the software ‘ 3D Route Builder ‘ in which the planned trip shall be loaded: it produces an excel file which contains altitude information.
  This approach doesn’t use real – driving data but it is based on the trip definition computed before the RDE test.

ID 58				
Parameter	**Unit**	**Matlab tool validation**	**Matlab PEMS emulation 1st approach**	**Matlab PEMS emulation 2nd approach**
Minimum Altitude	m	273.4	262.3	268.0
Maximum Altitude	m	410.3	405.0	410.0
Difference start - end	m	7.4	10.2	12.0

Table 24 - Matlab routine - Emulation tool – Bound. Cond. – I & II approaches ID 58

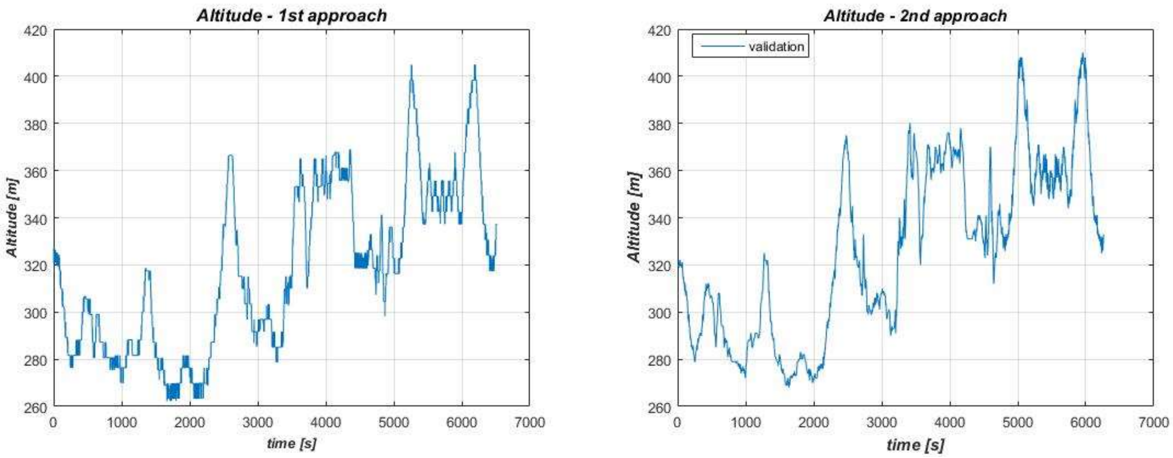


Figure 21 - Matlab routine - Emulation tool – Bound.Cond. – Altitude - Approach 1&2 ID58

It is noticed that the shape related to time and the absolute values of altitude are similar for the two approaches: this is possible thanks to the formula calibration made based on the starting trip altitude.
In the tool the 1st approach has been chosen because it is more real than the 2nd approach because it lets to collect real - driving data.
Moreover absolute, and not relative errors, are computed, because of the presence of small absolute values of the parameters taken in exam (percentage errors lose sense because highly affected by the small value put as denominator).

VALIDATION – PEMS EMULATION ABSOLUTE ERRORS					
Parameter	**Unit**	**ID 58**	**ID 61**	**ID 213**	**Average**
Minimum Temperature	degC	0.49	1.37	0.66	**0.84**
Maximum Temperature	degC	4.24	4.02	0.80	**3.02**
Minimum Altitude	m	11.10	0.30	9.60	**7.00**
Maximum Altitude	m	5.30	6.40	12.60	**8.10**
Difference start - end	m	2.80	18.10	24.20	**15.03**

Table 25- Matlab routine - Emulation tool – Boundary conditions – Absolute Errors

For future application it can be noticed that a third solution can be developed consisting in recording the trip online with a mobile phone with GPS using particular applications (such as “Locus Map”), converting it in an excel file with the usage of the software 3D Route Builder and reading it with Matlab.
It allows to record altitude data with lower frequency (0.2 Hz) but it is able to exceed the limit of the lack of online measurement present the 2nd approach as it has been explained before.

Cumulative Positive Elevation Gain

In order to calculate the total and the urban cumulative positive elevation gain time, vehicle speed and altitude information are required.
It is chosen the altitude defined with the first approach (from atmospheric pressure) because for this calculation instantaneous altitude values for each second are required.
Elevation gain computed with GPS altitude (validation tool) is really similar to the elevation gain computed with altitude calculated by pressure (emulation tool) as it is shown in the table below.

VALIDATION – PEMS EMULATION % ERROR				
Parameter	**ID 58**	**ID 61**	**ID 213**	**Average**
Total Cumulative Positive Elevation Gain	3.05	2.46	6.12	**3.88**
Urban Cumulative Positive Elevation Gain	2.12	2.06	3.81	**2.66**

Table 26- Matlab routine - Emulation tool – Cumulative Positive Elevation Gain – % Errors

In this section of the script the plot of the second road grades and discrete altitude versus the driven distance is produced to show the altitude profile of the trip.

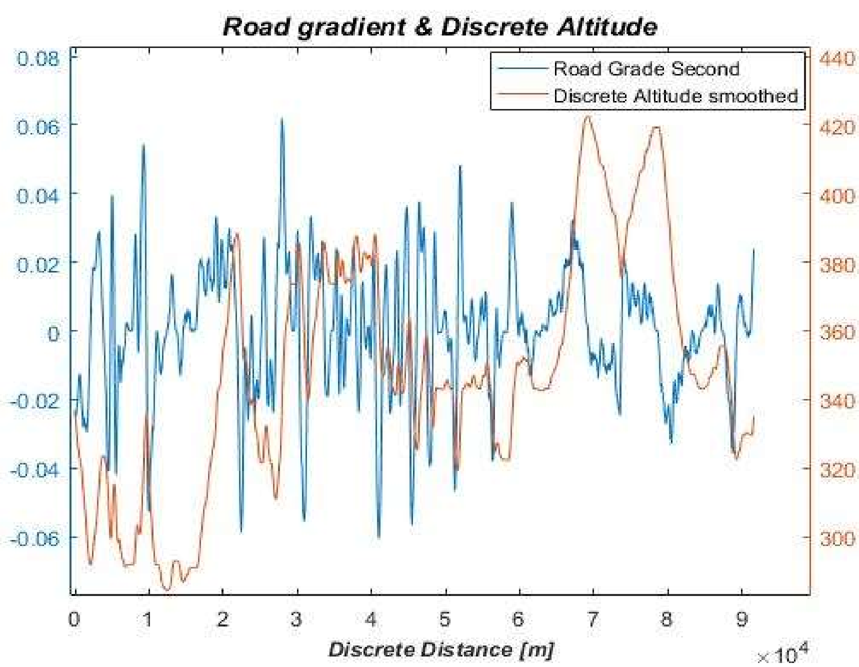


Figure 22 - Matlab routine – Emulation tool – CPEG - Road grade & Discrete Altitude ID211

This part of the Matlab script can be used also to determine the road gradient: in order to understand which method is more precise (altitude data from GPS or data from atmospheric pressure formula), how many times is better to smooth (two as it is written in the regulation or one) and which filtering is more accurate (± 200 meters as suggested by the regulation or ± 50 or 100 meters) in its determination, a comparison between the indicated torque measured by the ECU and the indicated torque determined by a vehicle model which receives road gradient information as input (already developed in the company) can be done for the different cases. The final goal of this comparison is to find the case which determines the best fit between the two torques obtained in different ways analyzing the least mean square error computed with three different RDE test data and considering its average.

Method	**Least mean square error: one smooth ([N*m]^2)**		
	ID 37	**ID 39**	**ID 40**
GPS ± 200 meters	499	487	494
GPS ± 100 meters	472	459	415
GPS ± 50 meters	514	501	396
Formula ± 200 meters	529	566	582
Formula ± 100 meters	634	674	698
Formula ± 50 meters	1056	1127	1099

Method	**Least mean square error: two smooths ([N*m]^2)**		
	ID 37	**ID 39**	**ID 40**
GPS ± 200 meters	531	517	528
GPS ± 100 meters	468	456	425
GPS ± 50 meters	494	483	397
Formula ± 200 meters	507	527	545
Formula ± 100 meters	462	496	520
Formula ± 50 meters	687	753	749

Method	**Average least mean square error ([N*m]^2)**	
	Two times smooth	**One time smooth**
GPS ± 200 meters	525	493
GPS ± 100 meters	450	448
GPS ± 50 meters	458	471
Formula ± 200 meters	526	559
Formula ± 100 meters	493	668
Formula ± 50 meters	730	1094

Table 27 - Matlab routine – Emulation tool - Road grade – Least mean square errors

First of all it shall be considered that, with the same filtering, GPS data give more accurate results (inferior least mean square error).
Moreover the approach characterized by two smooths produces similar results if GPS data are considered as it is better if formula data are taken into account.
Finally a filtering of ± 100 meters is preferable if altitude is measured by GPS whatever is the number of smooths as a ± 100 or ± 200 meters filtering is the most precise if formula is applied depending on the number of smooths.
Definitely the best solution to determine road gradient is to acquire data with GPS (if it is possible) and filtering them with an interval of ± 100 meters.
In the graphic below the distribution of the torque measured by ECU (experimental) and the torque defined by the model (simulated) is plotted in the same graphic with the diagonal in order to understand how much close the experiment and the model are.

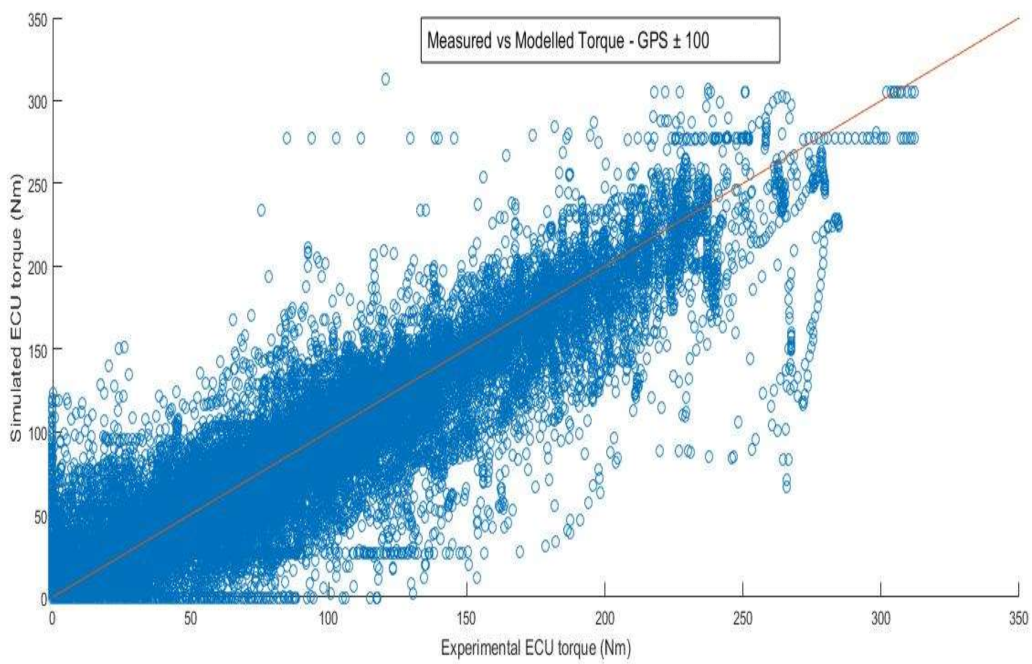


Figure 23 - Matlab routine – Emulation tool - Road gradient determination – Measured vs Modelled Torque ID 37

It is important to notice that this analysis is only a small part of the study which has to be done about the simulation model to understand which are all the different parameters which causes discrepancies between the experimental torque measured by the ECU and the modelled one.
For this reason the numerical errors presented above shall not be considered in absolute terms but only as a relative comparison between the different methods in the road gradient determination.

Dynamics requirements

In v*apos [95] and RPA calculation the only parameter needed as input is the vehicle speed: in this new routine it is taken from the ECU sensor and not anymore from the GPS signal.

VALIDATION – PEMS EMULATION % ERROR				
Parameter	**ID 58**	**ID 61**	**ID 213**	**Average**
Number of urban bins	0.95	0.42	0.76	**0.71**
Number of rural bins	0.62	3.80	1.96	**2.13**
Number of motorway bins	7.98	4.62	0.27	**4.29**
v*a pos [95] urban	0.89	0.46	0.42	**0.59**
v*a pos [95] rural	2.14	1.74	0.20	**1.36**
v*a pos [95] motorway	5.49	1.22	7.09	**4.60**
RPA urban	0.33	0.94	0.96	**0.74**
RPA rural	2.35	0.93	0.15	**1.14**
RPA motorway	0.33	0.57	0.58	**0.49**

Table 28- Matlab routine - Emulation tool – Dynamics requirements – % Errors

Percentage errors higher than 5 % happen because of the difference in vehicle speed recording from GPS and ECU as it has been explained in the paragraph regarding the general requirements. Vehicle speed errors cause acceleration errors which affect v*a pos [95] calculation in particular regarding the motorway part of the trip (higher vehicle speed).
In this section of the script plots of the v*a pos [95] and RPA limits are presented in order to understand how far is the specific ID from the dynamics requirements imposed by regulation.

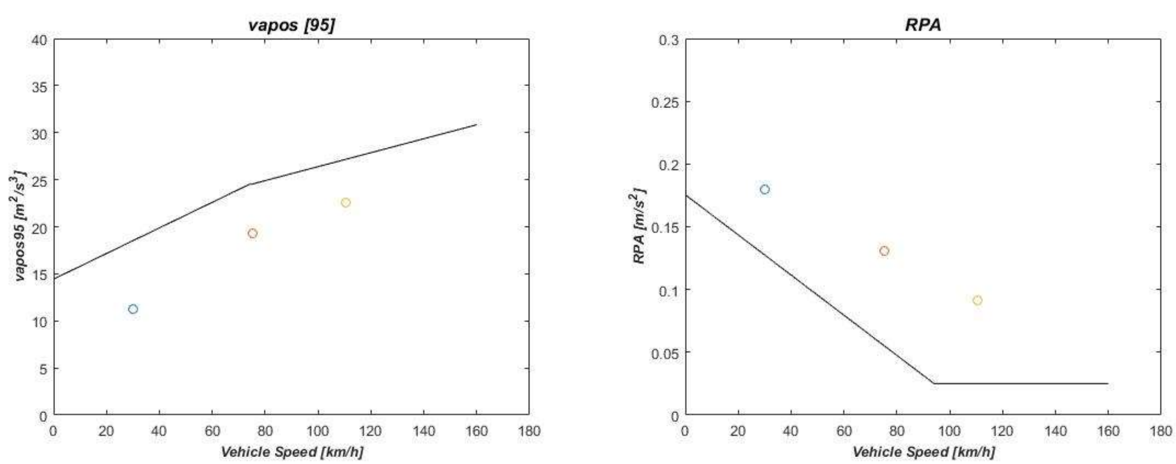


Figure 24 - Matlab routine - Emulation tool – Dyn. Req. – vapos [95] & RPA graphics ID 58

Power Binning method

In Power Binning method the following parameters are required as input information:

- Time;
- Instantaneous vehicle speed;
- k & D: slope and intercept of P_w / CO_2 graphic of the specific vehicle during a WLTC. They are obtained interpolating the average wheel power and CO_2 emission for each phase (low, medium, high and extra-high) of the cycle.
- CO_2 instantaneous emissions: they are not anymore measured by PEMS analyzer but they are obtained from a formula depending on the demanding quantity of injected fuel calculated by the ECU and on the engine speed measured by sensors:

$$CO_{2\ i} = 3.14 * fqd_{i-1} * enginespeed_i * 0.12$$

- ✓ $CO_{2\ i}\ \left[\frac{g}{h}\right]$ = CO_2 instantaneous emission for each time instant i;
- ✓ 3.14 = experimental coefficient to compute CO_2 emissions from fuel quantity for diesel engine (3.04 for gasoline engine);
- ✓ $fqd_{i-1}\ \left[\frac{\text{mg}}{\text{stroke}}\right]$ = fuel quantity demand of the previous time instant (i-1);
- ✓ $enginespeed_i\ [rpm]$ = engine speed of the time instant i;
- ✓ 0.12 = factor to convert the input units of measurements ($\frac{\text{mg}}{\text{stroke}}\ x\ rpm$) into the output ones ($\frac{g}{h}$).

Source: 2017/1151 (page 632) (considering ideally that all HC and CO convert into CO2)

In order to validate the previous formula five WLTC tests have been done in a controlled laboratory (VEL or Windtunnel) in order to compare PEMS and VEL or Windtunnel measurements with formula results.
Only a small change has been done in the CO_2 calculated in Matlab to make it more reliable: all negative values have been set to 0 (because they derived from not realistic negative engine speed values measured by sensor at the beginning of the acquisition).
Two different types of WLTC laboratories results are presented: CO_2 emissions measured tailpipe (available for each time instant) and the total value of CO_2 emitted measured by bags (only the final total measure is available).
This has been done because the instantaneous values measured tailpipe give the possibility to compare results for each second and the bags result is the measurement which is taken as reference.
In ID 219 VEL tailpipe CO_2 emission have been computed manually to take into account an offset which occurred in the exhaust flow measurement between VEL and PEMS due to a problem in the VEL equipment calibration: the correctness of these new calculation is confirmed by the perfect match between bags and tailpipe VEL final results.

ID	Parameter	Unit	Matlab FORMULA	VEL or WT BAGS	VEL or WT TAILPIPE	PEMS TAILPIPE
ID 210	Total CO_2 emitted	g	2488.71	2568.20	2712.57	-
	% Error with Matlab formula	%	0	**3.19**	9.00	-
ID 211	Total CO_2 emitted	g	2532.03	2542.28	2649.50	2791.47
	% Error with Matlab formula	%	0	**0.40**	4.64	10.25
WLTC at -7 degC	Total CO_2 emitted	g	2929.72	2942.01	2941.19	-
	% Error with Matlab formula	%	0	**0.42**	0.39	-
WLTC at 23 degC	Total CO_2 emitted	g	2673.20	2654.23	2602.50	-
	% Error with Matlab formula	%	0	**0.71**	2.64	-
ID 219	Total CO_2 emitted	g	2566.81	2539.58	2531.46	2673.22
	% Error with Matlab formula	%	0	**1.06**	1.38	4.15

Table 29 - Matlab routine - Emulation tool – WLTC CO_2 analysis – Formula, VEL & PEMS

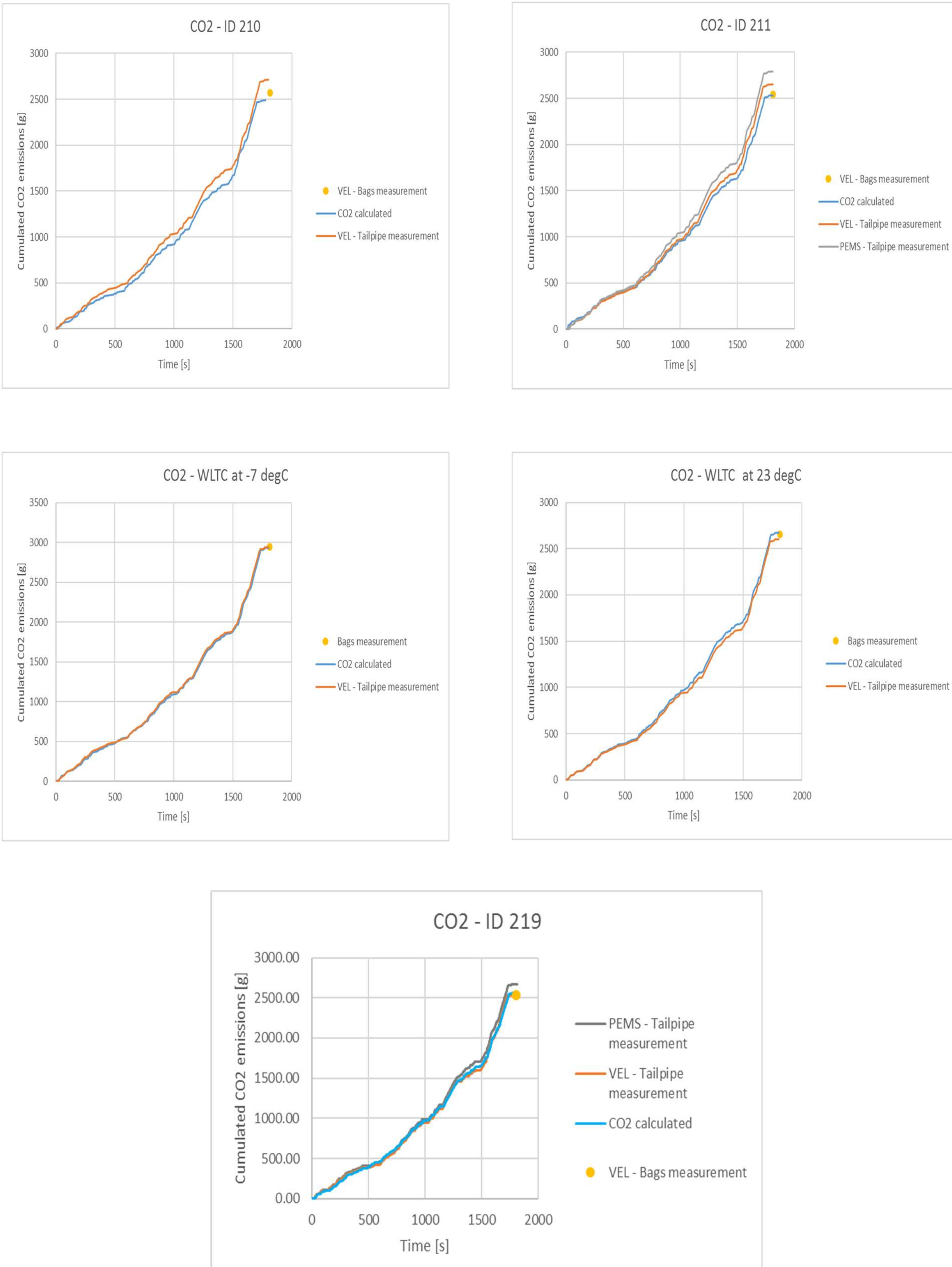


Figure 25 - Matlab routine - Emulation tool – WLTC CO_2 analysis - CO_2 [g] vs time

The results show that the formula implemented in Matlab predicts correctly the real amount of CO_2 emitted because results are close to bags measurement (1 % of average error) and the shape of CO_2 related to time is the same as PEMS and VEL tailpipe measurements.
Moreover it is evident that the PEMS does not measure CO_2 properly because PEMS tailpipe measurements are quite different to VEL tailpipe measurement (6 % of relative error) and VEL bags measurement (8 %).

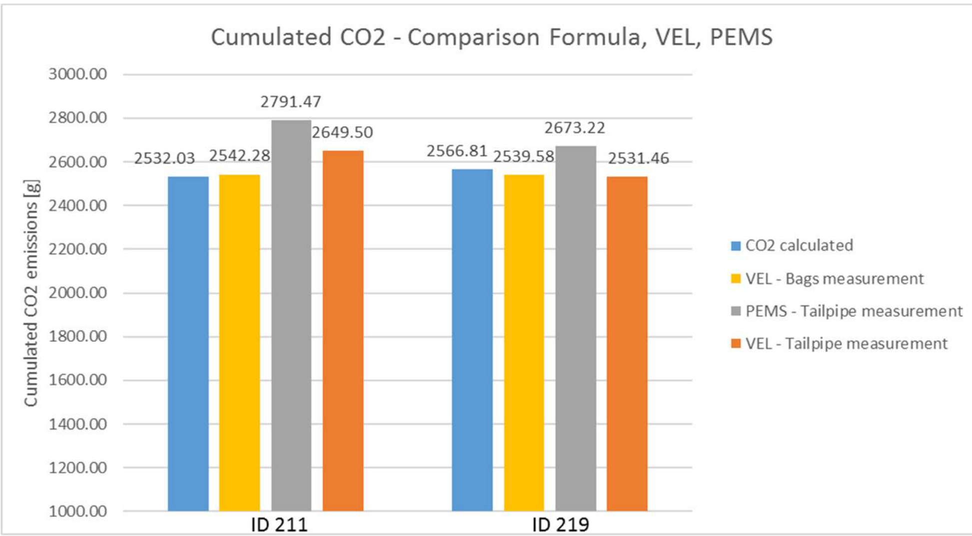


Figure 26 - Matlab routine - Emulation tool – WLTC CO_2 analysis – Formula, VEL & PEMS

It is useful to compare matlab results with PEMS measurements, when they are available (only in ID 211 and in ID 219), to quantify the differences in the input information for Power Binning method between Matlab validation tool and Matlab PEMS Emulation tool and to explain why the two tools ('Validation' which receives PEMS information as input and 'PEMS emulation' which receives CO_2 formula as input) give different results in the Power Binning and MAW method.

FORMULA – PEMS MEASUREMENTS: % ERROR in WLTC TESTS		
Parameter	**ID 211**	**ID 219**
Total CO_2 emitted	10.25	4.15

Table 30 - Matlab routine - Emulation tool – WLTC CO_2 analysis – Sensor & PEMS

The difference between the total amount of CO_2 emitted detected by the experimental formula and the PEMS analyzer is highly present in the RDE taken in exam, too.
This is the first reason which explain why Power Binning and MAW results defined by the two tools are different.

FORMULA – PEMS MEASUREMENTS: % ERROR in RDE TESTS				
Parameter	**ID 58**	**ID 61**	**ID 213**	**Average**
Total CO_2 emitted	5.40	3.47	6.16	**5.01**

Table 31- Matlab routine - Emulation tool – RDE CO_2 analysis – Sensor & PEMS

In addition to this cause, Power Binning results produced by the two different tools are different because of differences in the evaluation of the parameters k and D (slope and intercept of the graphic CO_2/P_w related to a WLTC test).
In the 'Validation tool' they are given by Horiba PC as in the 'PEMS Emulation tool' they are calculated starting from a previous WLTC.
This difference is caused by different calculation process because they both receive input information from the same WLTC (Horiba receives as input only the grams of CO_2 emitted for each WLTC phase as the PEMS emulation receives instantaneous CO_2 and P_w values for each time instant).

VALIDATION – PEMS EMULATION % ERROR				
Parameter	**Unit**	**Horiba**	**PEMS Emulation**	**% Error**
k	g/kWh	655.49	680.09	3.75
D	g/h	1811.28	1758.20	2.93

Table 32- Matlab routine - Emulation tool – Power Binning– k & D comparison

These two error sources produce high percentage errors comparing the results of the two tools.

VALIDATION – PEMS EMULATION % ERROR				
Parameter	**ID 58**	**ID 61**	**ID 213**	**Average**
Total bins Class 1	26.98	28.84	21.52	**25.78**
Total bins Class 2	6.72	0.00	9.61	**5.44**
Total bins Class 3	4.77	11.32	6.03	**7.37**
Total bins Class 4	3.73	10.60	0.94	**5.09**
Total bins Class 5	0.67	4.89	2.16	**2.57**
Total bins Class 6	5.56	2.17	5.13	**4.29**
Urban bins Class 1	20.63	18.99	16.61	**18.74**
Urban bins Class 2	6.34	3.11	7.79	**5.75**
Urban bins Class 3	6.18	10.98	6.66	**7.94**
Urban bins Class 4	18.23	25.38	6.60	**16.74**
Urban bins Class 5	23.81	3.70	25.00	**17.50**

Table 33- Matlab routine - Emulation tool – Power Binning– % Errors

This subject has not further examined because Power Binning method will disappear with the new regulation (RDE Pack 4).

MAW method & NOx emissions (RDE Pack 3)

In MAW method the following parameters are required as input information:

- Time;
- Instantaneous vehicle speed (sensor);
- Instantaneous driven distance (calculated);
- CO_2 instantaneous emissions (calculated);
- NO_x instantaneous emissions.

NOx instantaneous emissions are measured towards a NOx tailpipe sensor which measures NOx in ppm for each second of the test.
This value has to be converted in g/s using the exhaust mass flow estimation:

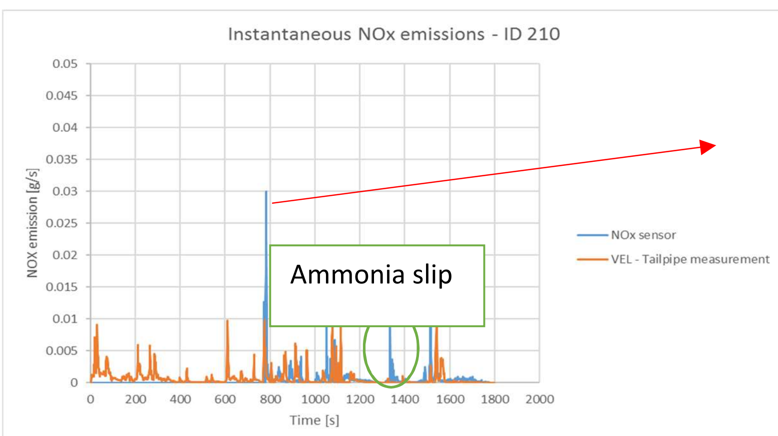
$$NO_x\left[\frac{g}{s}\right] = Exh_{MassFlow}\left[\frac{kg}{s}\right] * NO_x[ppm] * u_{NOx,diesel}$$

- $Exh_{MassFlow}$ is the exhaust muffler flow estimate (sum of air and fuel flow);
- $NOx\ [ppm]$ is the quantity measured by the sensor;
- $u_{NOx,diesel}$ is the ratio of the density of the exhaust component gas (in this case NOx) and the overall density (in this case diesel density = 1.2943 kg/m^3): 0.001586 (value given by the regulation).

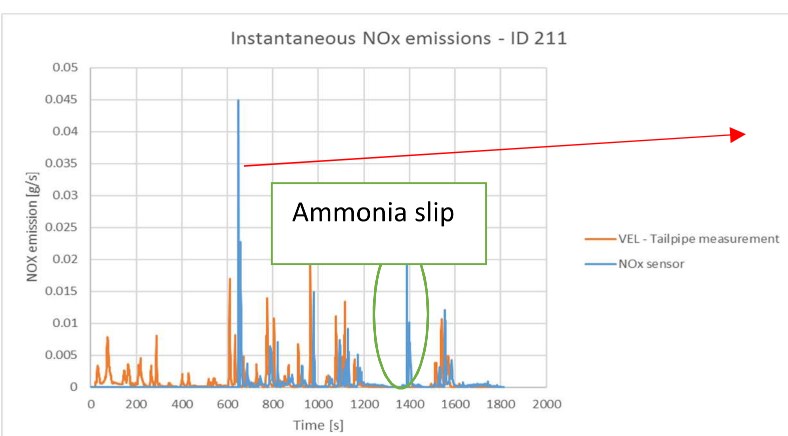
In order to establish the precision of the approach used, NOx analysis has been done for five WLTC tests driven in laboratory (the same as CO_2 analysis).
First of all it shall be considered that NOx negative values measured by NOx sensor have not been set to zero: this choice has been done because negative values happen because of sensor noise which produce random results and, so, near to the zero there are some positive and some negative noise values which, theoretically, compensate each other.
For CO_2 analysis this problem has been studied in a different way because negative values derived from negative engine speed measured by the sensor at the beginning of the test which is not a realistic event but it is only a problem of measurement.
In the sensor analysis two problems and error sources occur.
The first problem of this approach is that NOx sensor is not working for about the first 550/600 seconds of the test (time interval highly influenced by the test temperature): for this reason in this first test period NOx emissions (ppm) shall be determined using a NOx estimator which is a model previously developed and validated in Delphi in order to estimate emissions depending on real driving conditions.
This model is characterized by an estimation of NOx engine out emissions [ppm] and two SCR efficiencies (the Honda T113 taken in exam has an SDPF and an SCR to reduce NOx) which can be used to estimate NOx tailpipe emissions [ppm]:

$$NO_{x,tailpipe}\,[\,ppm\,] = NO_{x,engineout}\,[\,ppm\,] * \left(1 - SDPF_{efficiency}\right) * \left(1 - SCR_{efficiency}\right)$$

It has been chosen to use NOx estimator values for the first 600 seconds or more, depending on the test temperature, to be sure to avoid the first wrong measurement made by the NOx sensor which occurs as soon as it starts to work (not realistic peak present in almost every tests).
The choice of the time interval in which the NOx estimator shall be used, has been done for every tests independently: instantaneous NOx emission [g/s] measured by the NOx sensor have been compared with the emissions measured by VEL tailpipe (considered as reference) as it is explained by the graphics below.
The second problem of the NOx sensor is that it measures NOx + NH_3: for this reason there is the possibility to have the presence of peaks that in reality are not NOx peaks but are caused by ammonia slip: this phenomena occurs when SCR is full of NH_3 and a sudden temperature change happens causing a SCR capacity drop: this brings all the excess NH_3 to slip.
This is evident in ID 210, ID 211 and in the WLTC at -7 degC at about 1400 seconds.
It is important to consider that, in order to compare sensors, PEMS and VEL/WT measurements, VEL/WT results shall be corrected dividing the measurements for an instantaneous coefficient factor KH which depends on ambient temperature, pressure and relative humidity.
This happens because VEL measurements are automatically corrected multiplying measurement with KH to take into account humidity in order to obtain results valid for the regulation as sensors and PEMS measurements are not corrected: the accuracy of this approach is confirmed by the perfect match between VEL and PEMS measurements which can be noticed for ID 211 in the graphic of cumulated NOx related to time.



NOx unrealistic peak measured by the sensor before 800 seconds: estimator analysis considered between 0 and 800 seconds.



NOx unrealistic peak measured by the sensor before 700 seconds: estimator analysis considered between 0 and 700 seconds.

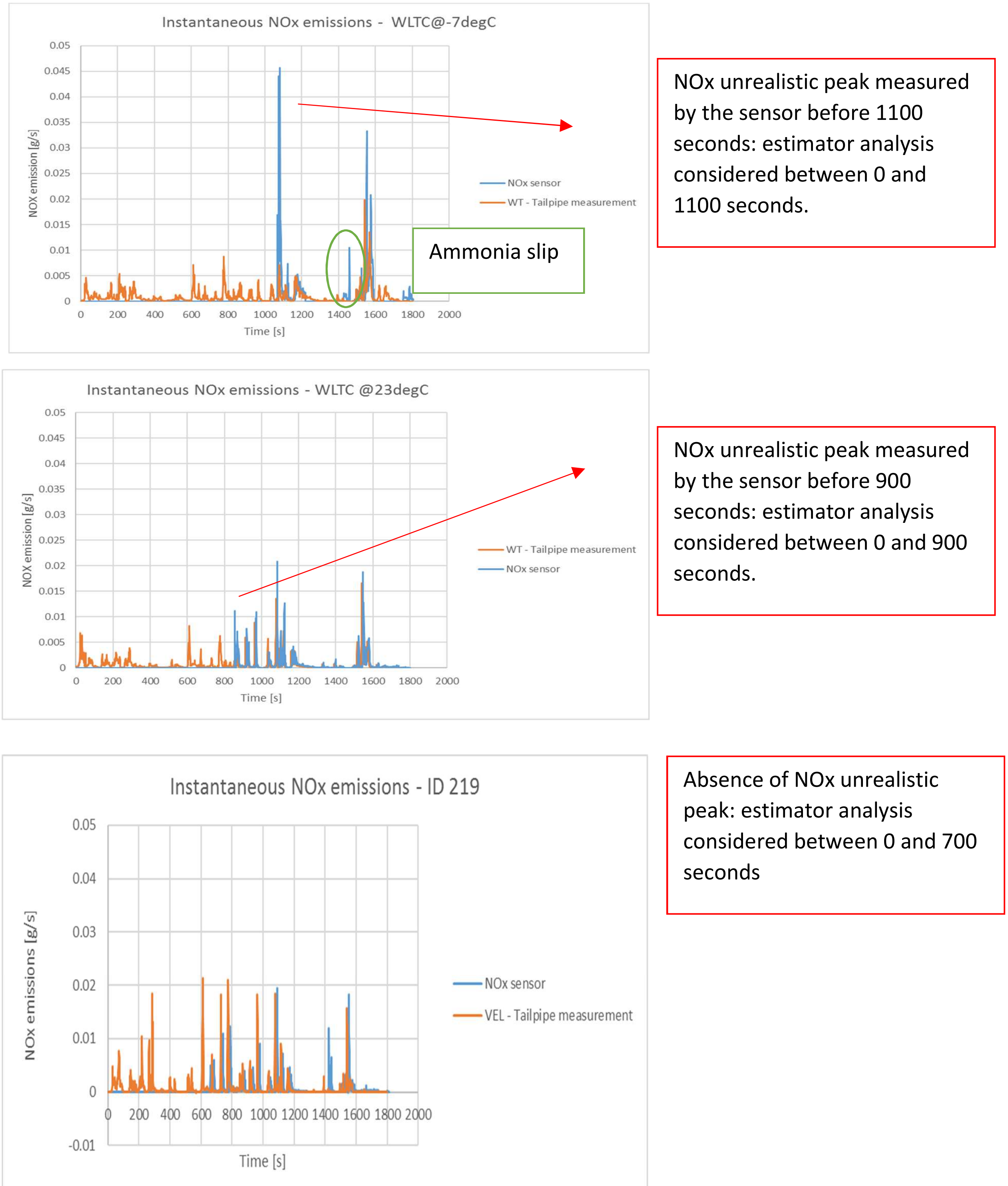
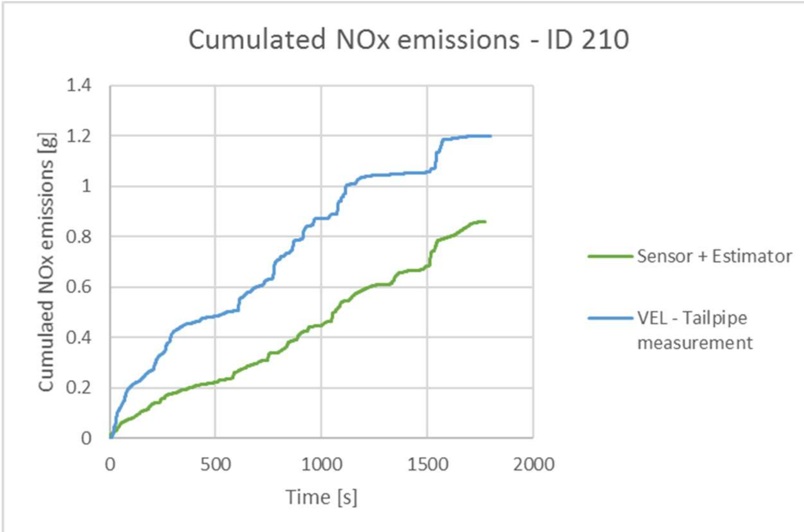
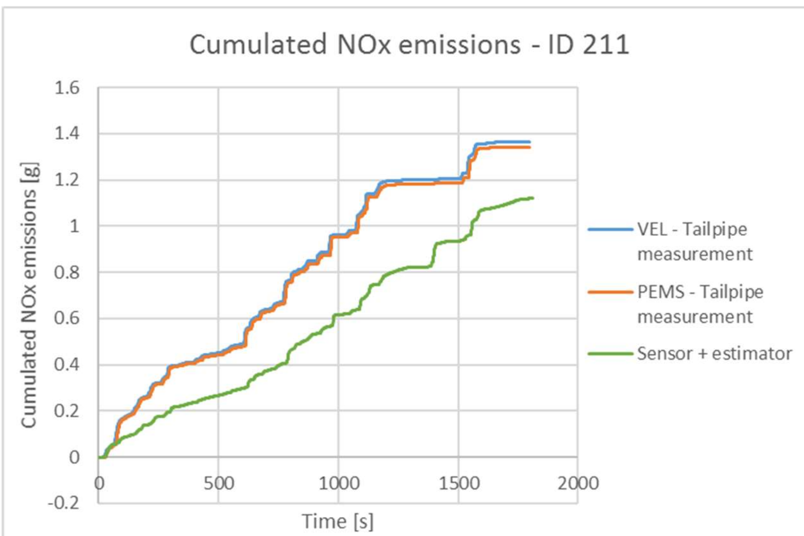


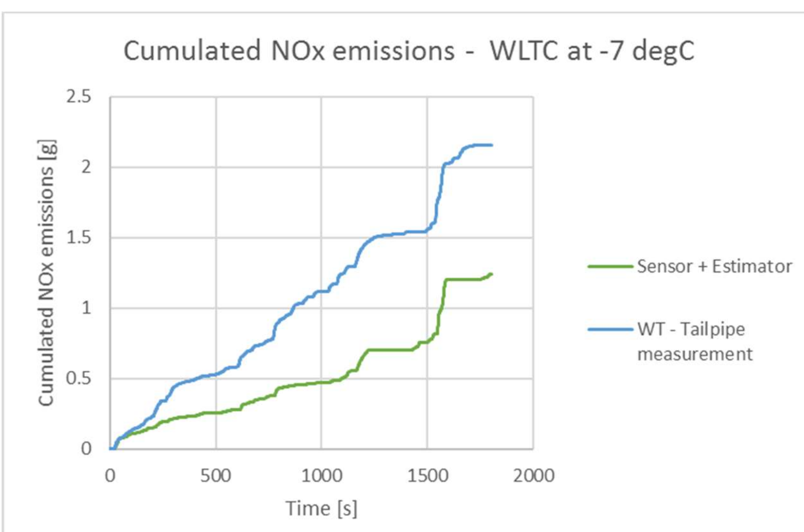
Figure 27 - Matlab routine - Emulation tool – WLTC NOx analysis – NOx [g/s] vs time

ID	Parameter	Unit	Sensor + Estimator	VEL or WT Bags measurement	VEL or WT Tailpipe measurement	PEMS Tailpipe measurement
ID 210	Total NOx emitted	mg	860.4	1068.9	1200.1	-
	% Error with sensor + estimator	%	0	24.23	39.48	-
ID 211	Total NOx emitted	mg	1119.1	1229.9	1366.5	1342.5
	% Error with sensor + estimator	%	0	9.90	22.11	20.00
WLTC at -7 degC	Total NOx emitted	mg	1243.6	2290.8	2157.0	-
	% Error with sensor + estimator	%	0	84.21	73.45	-
WLTC at 23 degC	Total NOx emitted	mg	1023.2	1342.5	1146.7	-
	% Error with sensor + estimator	%	0	31.21	12.07	-
ID 219	Total NOx emitted	mg	966.6	1320.9	1478.8	1592.4
	% Error with sensor + estimator	%	0	36.56	52.99	64.74

Table 34 - Matlab routine - Emulation tool – WLTC NOx analysis – Sensor, VEL & PEMS


Cumulated NOx emissions - ID 210
Cumulaed NOx emissions [g]
Time [s]
Sensor + Estimator
VEL - Tailpipe measurement


Cumulated NOx emissions - ID 211
Cumulated NOx emissions [g]
Time [s]
VEL - Tailpipe measurement
PEMS - Tailpipe measurement
Sensor + estimator


Cumulated NOx emissions - WLTC at -7 degC
Cumulated NOx emissions [g]
Time [s]
Sensor + Estimator
WT - Tailpipe measurement

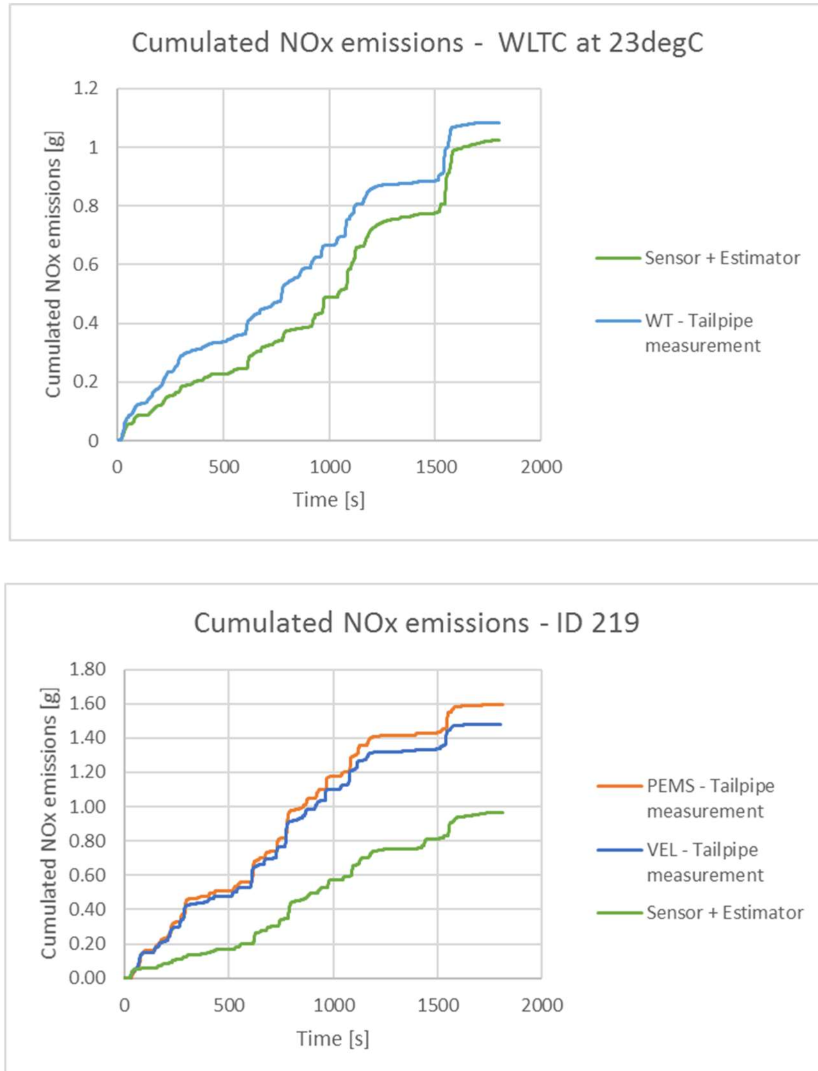


Figure 28 - Matlab routine - Emulation tool – WLTC NOx analysis –NOx [g] vs time

These results show that the PEMS is measuring NOx quite correctly (5 % of difference with VEL – tailpipe measurement which can be considered the reference) as Matlab analysis doesn't predict very well NOx emissions (40 % of error) even if the shapes of the cumulated NOx [g] vs time are really similar.
Sensor + estimator analysis shall be compared to VEL tailpipe measurement because they are both in tailpipe position and they both measure continuously.
The difference between them is high and it is mainly due to the first period in which the NOx estimator is underestimating NOx emission.
These % errors will decrease in the future thanks to the technological improvement in NOx sensors and estimators.
The analysis of WLTC in VEL/WT lets us to confirm the reliability of the PEMS analyzer results in order to take the Matlab "Validation Tool" (which considers PEMS analyzer NOx measurements) as reference in the following RDE tests in which VEL measurements are not present.

The difference between "sensor + estimator" analysis and PEMS measurement is presented below:

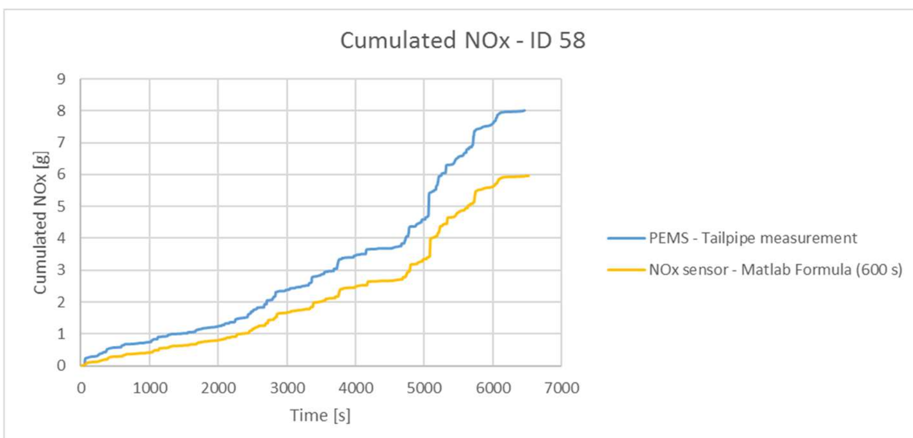
SENSOR + ESTIMATOR – PEMS MEASUREMENTS: % ERROR in WLTC TESTS		
Parameter	**ID 211**	**ID 219**
Total NOx emitted	20.00	64.74

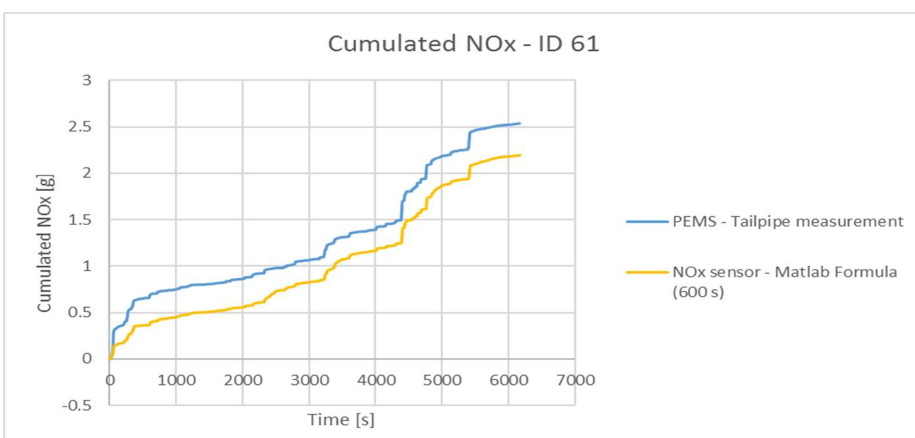
Table 35 - Matlab routine - Emulation tool – WLTC NOx analysis – Sensor & PEMS

This high difference is also present in the RDE tests taken in exam:

SENSOR + ESTIMATOR – PEMS MEASUREMENTS: % ERROR in RDE TESTS (estimator for 600 seconds)				
Parameter	**ID 58**	**ID 61**	**ID 213**	**Average**
Total NOx emitted	25.57	13.51	19.75	**19.61**

Table 36 - Matlab routine - Emulation tool – RDE NOx analysis – Sensor & PEMS





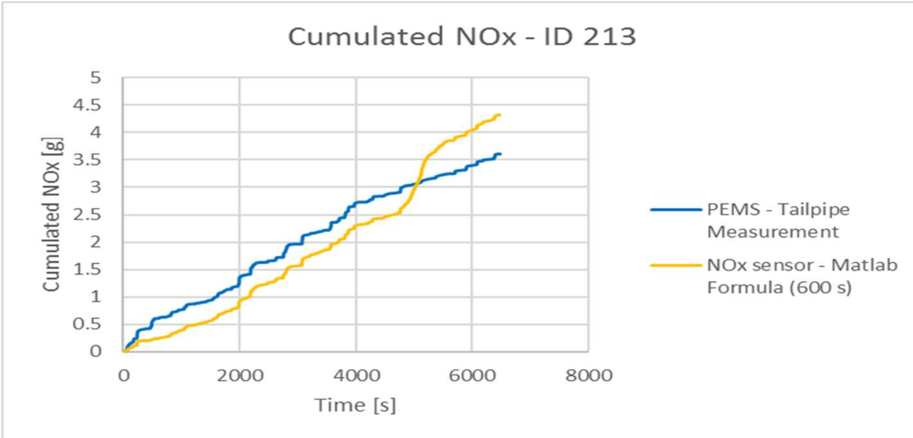


Figure 29 - Matlab routine - Emulation tool – RDE NOx analysis – Sensor & PEMS

In ID 58, ID 61 and ID 213 analysis it has been noticed that the unreal peak of NOx measured by the NOx sensors occurs at about 500 seconds: for this reason, to minimize the NOx estimation period (which is an important error source in the final evaluation of emissions), estimator measurements are considered for only the first 600 seconds.
The three tests analyzed shows that the NOx estimator underestimates NOx emission: this difference can increase as in ID 58, be constant as in ID 61 or decrease as in ID 213: in particular the shape of ID 213 is not real because there is an huge step at about 5000 seconds caused by ammonia slip and not by NOx emissions (in fact it is not detected by the PEMS analyzer which measures only NOx without taking into account NH_3 emissions).

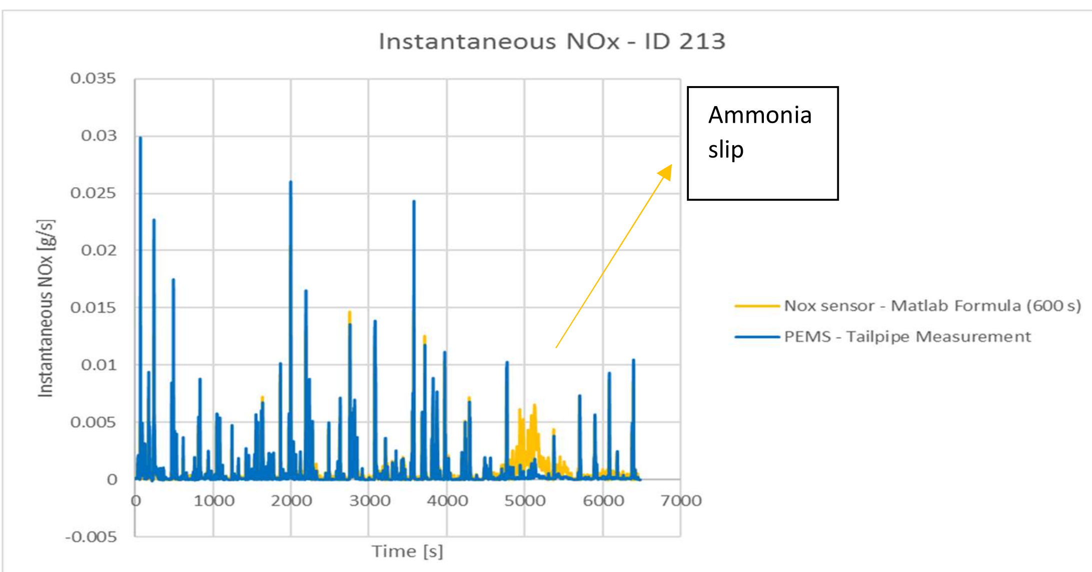


Figure 30 - Matlab routine - Emulation tool – RDE NOx analysis - PEMS & Sensor ID213

Because of measurement problems described up to now regarding ve hicle speed, CO_2 and NOx instantaneous emissions, MAW final results are really different compared to the results obtained using PEMS information as input.
In particular errors in the window distribution are a consequence of a different vehicle speed (less urban and more rural and motorway windows because vehicle speed detected by ECU is higher than the one detected by GPS as the total number of windows is almost constant because it is small affected by CO_2 emissions), errors in the number of normal windows are consequence of different instantaneous CO_2 emissions (lower CO_2 instantaneous emissions cause more normal windows because some points which were out the valid bandwidth are shifted further down and get inside it) and errors in NOx total and urban emissions are a consequence of different NOx instantaneous emissions (NOx estimator underestimates NOx emissions and NOx sensor takes into account NH_3, too).

VALIDATION – PEMS EMULATION % ERROR				
Parameter	**ID 58**	**ID 61**	**ID 213**	**Average**
Urban windows	4.77	1.69	10.63	**5.70**
Rural windows	1.47	0.32	6.74	**2.84**
Motorway windows	3.44	0.39	0.33	**1.39**
Total windows	0.02	0.26	0.28	**0.19**
Urban ratio	4.75	1.42	10.37	**5.51**
Rural ratio	1.48	0.58	7.05	**3.04**
Motorway ratio	3.46	0.64	0.58	**1.56**

Table 37 - Matlab routine - Emulation tool – MAW– Completeness - % Errors

VALIDATION – PEMS EMULATION % ERROR (Different Tol 1)				
Parameter	**ID 58**	**ID 61**	**ID 213**	**Average**
Tol 1	0.00	13.79	7.41	**7.07**
Urban normal windows	6.35	8.25	4.20	**6.27**
Rural normal windows	65.40	2.13	49.65	**39.06**
Motorway normal windows	24.65	5.46	12.01	**14.04**
Urban normal ratio	11.68	10.12	7.19	**9.66**
Rural normal ratio	63.00	1.80	40.20	**35.00**
Motorway normal ratio	20.52	5.04	11.63	**12.40**

Table 38 - Matlab routine - Emulation tool – MAW– Normality - % Errors (Different Tol 1)

Normality analysis described up to now shall be improved considering the same tolerance (same bandwidth inside which a window is considered normal) in order to obtain coherent results:

VALIDATION – PEMS EMULATION % ERROR (Same Tol 1)				
Parameter	**ID 58**	**ID 61**	**ID 213**	**Average**
Tol 1	0	0	0	**0**
Urban normal windows	6.35	20.03	4.20	**10.19**
Rural normal windows	65.40	8.84	66.12	**46.79**
Motorway normal windows	24.65	8.57	12.01	**15.08**
Urban normal ratio	11.68	22.11	7.19	**13.66**
Rural normal ratio	63.00	8.49	55.62	**42.37**
Motorway normal ratio	20.52	8.14	11.63	**13.43**

Table 39 - Matlab routine - Emulation tool – MAW– Normality - % Errors (Same Tol 1)

MAW graphics are plotted to show how all the points are shifted further down (more green points in MAW graphic of the “Emulation Tool”) because the average speed of each window is almost the same as their CO_2 emissions are lower as it is explained by the graphics below in which the average speed and the amount of CO_2 emission of each window for the two Matlab tools are compared.
For this reason in the “Emulation Tool” is easier to pass the normality check.

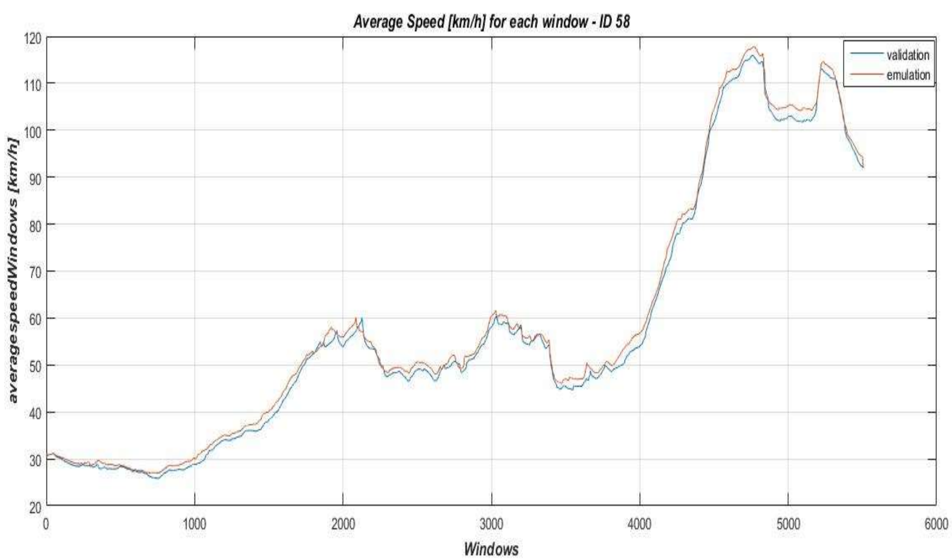


Figure 31 - Matlab routine - Emulation tool – MAW - Average speed of each window - ID58

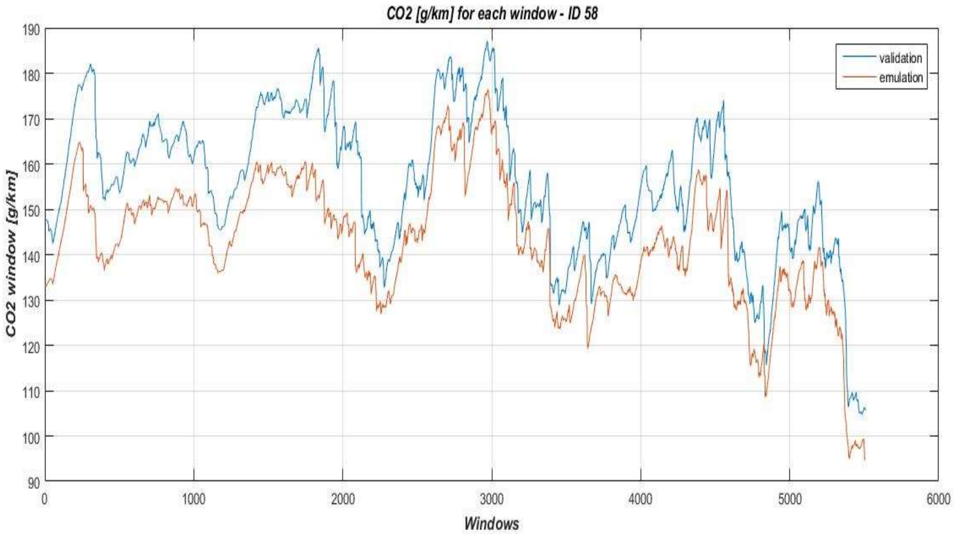


Figure 32 - Matlab routine - Emulation tool – MAW - CO_2 emissions of each window - ID58

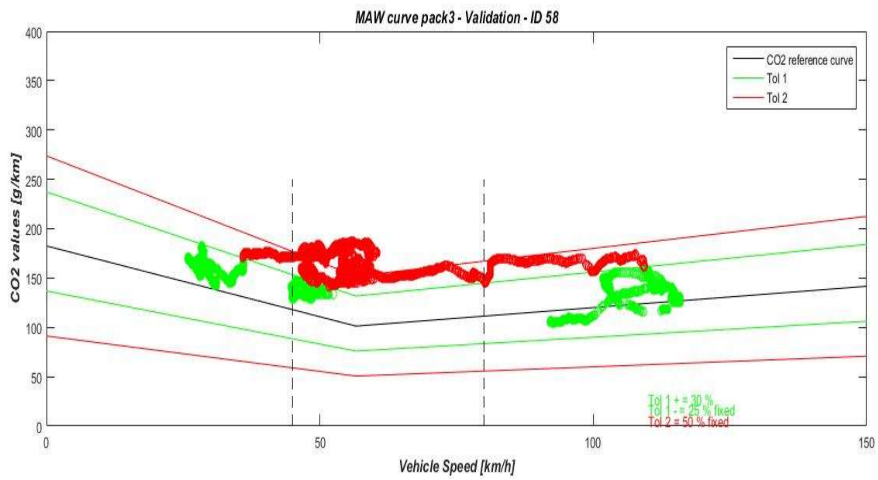


Figure 33 - Matlab routine - Emulation tool – MAW - Validation Tool - ID58

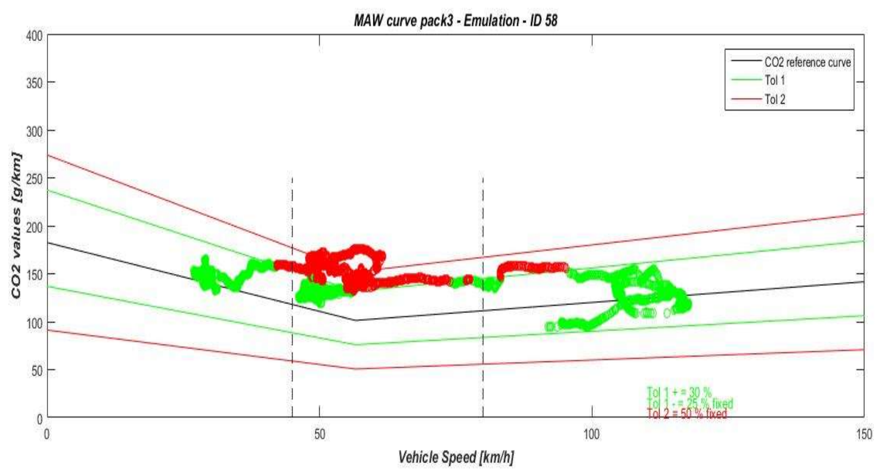


Figure 34 - Matlab routine - Emulation tool – MAW - Emulation Tool - ID58

Because of a different windows position in the MAW graphic (and so different multiplicative coefficients for the calculation of each window NOx emissions) and different measurement of instantaneous NOx emissions the final results of emitted NOx in g/km are quite different:

VALIDATION – PEMS EMULATION % ERROR				
Parameter	**ID 58**	**ID 61**	**ID 213**	**Average**
NOx Total emissions	21.76	13.40	12.37	**15.84**
NOx Urban emissions	26.08	19.16	12.10	**19.11**

Table 40 - Matlab routine - Emulation tool – NOx emissions - % Errors (Different Tol 1)

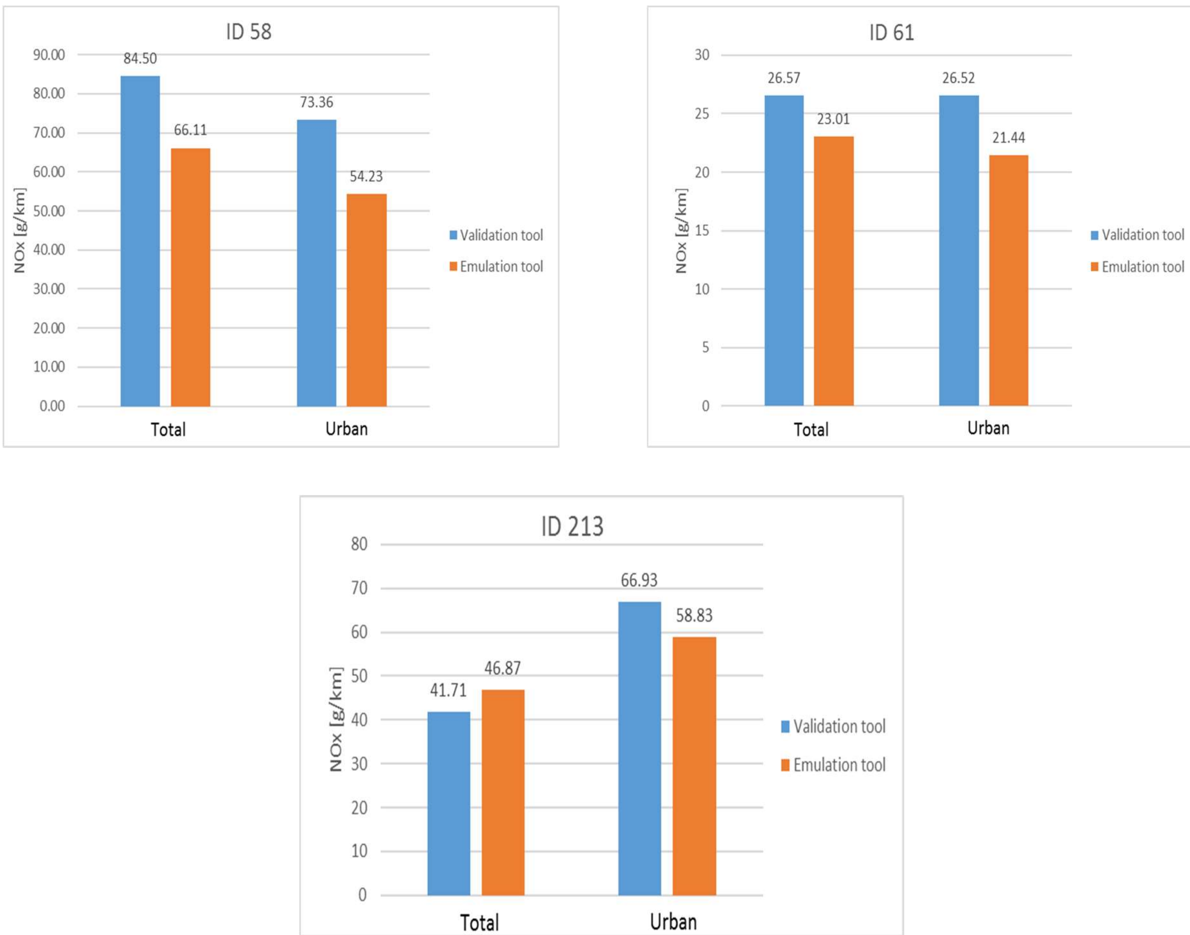


Figure 35 - Matlab routine - Emulation tool – NOx emissions - Validation vs Emulation

In ID 58 and ID 61 the emulation tool underestimates the final result of total and urban NOx MAW emissions because of the predominance of the effects of the reduction of NOx instantaneous emissions.

This is also valid for urban NOx MAW emissions in ID 213 as it is different for the total result in which the predominant effect becomes the presence of ammonia slip which causes an overestimation of the real result.

Pack 4

The last part of the matlab routine is the evaluation of MAW method and NOx total and urban emissions according the new RDE Pack 4 which will be valid for the beginning of 2019.
According the MAW method, RDE pack 4 will introduce two differences compared to pack 3.
First of all completeness check (i.e. at least 15% of urban, rural and motorway windows) will disappear because it has been noticed that it checks parameters that are yet limited with the condition on distance share.
Secondly there will be differences in the the bandwidths in which a window is defined as normal: changes in the reference line (black one) and in the first tolerance line (green one) and disappearance of second tolerance line (red one) as it has been explained in the first chapter related to the regulation.
Because of the introduction of differences between ICE and HEV vehicles in the RDE regulation, in the app interface of RDE Pack 4 the vehicle type shall be chosen (Number ‘1’ for ICE and ‘2’ for HEV vehicles).
The number of windows and its ratio in urban, rural and motorway will be the same as pack 3 but the number of normal windows will change.

Parameter	ID 58	ID 61	ID 213
Urban tolerance	45 % fixed	45 % fixed	45 % fixed
Rural and motorway tolerance	40 % fixed	40 % fixed	40 % fixed
Urban normal windows	1479	1257	1598
Rural normal windows	766	1345	2226
Motorway normal windows	1178	1236	1502
Urban normality ratio	91.52	80.06	100.00
Rural normality ratio	29.15	52.91	83.18
Motorway normality ratio	93.20	96.87	100.00

Table 41 - Matlab routine - Emulation tool – RDE Pack 4 – MAW Results

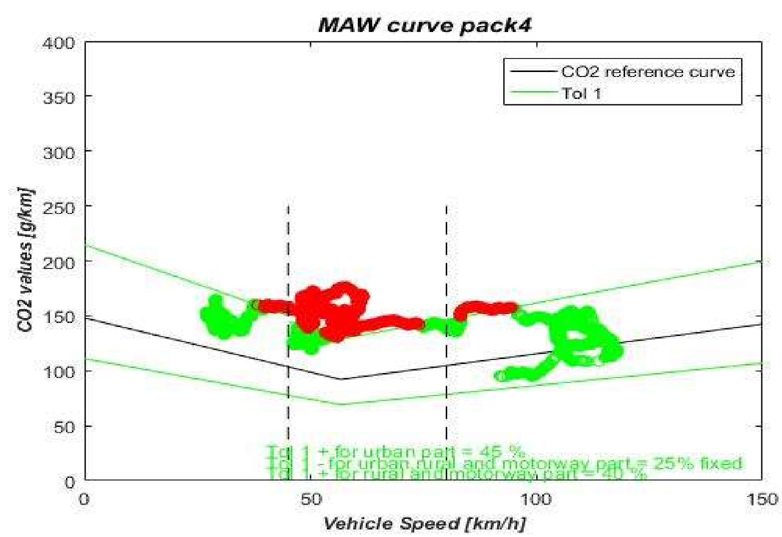


Figure 36 - Matlab routine - Emulation tool – RDE Pack 4 - MAW graphic - ID 58

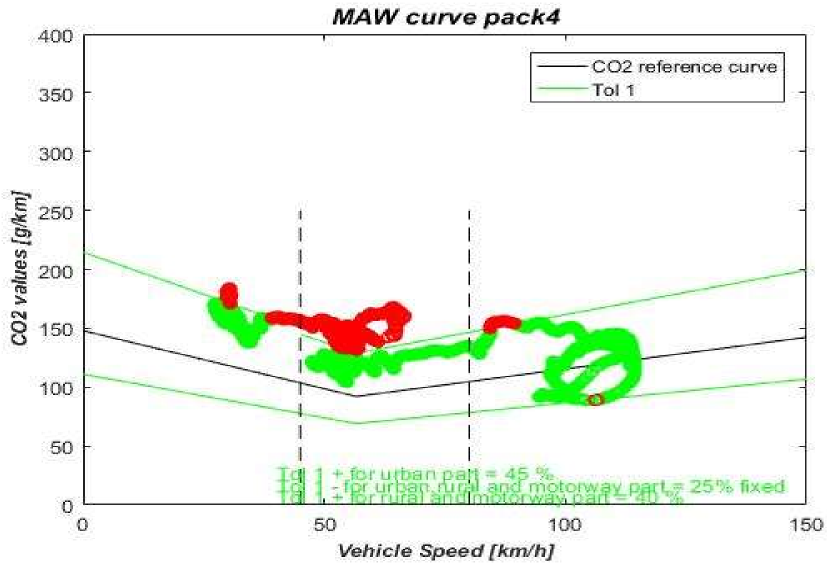


Figure 37 - Matlab routine - Emulation tool – RDE Pack 4 - MAW graphic - ID 61

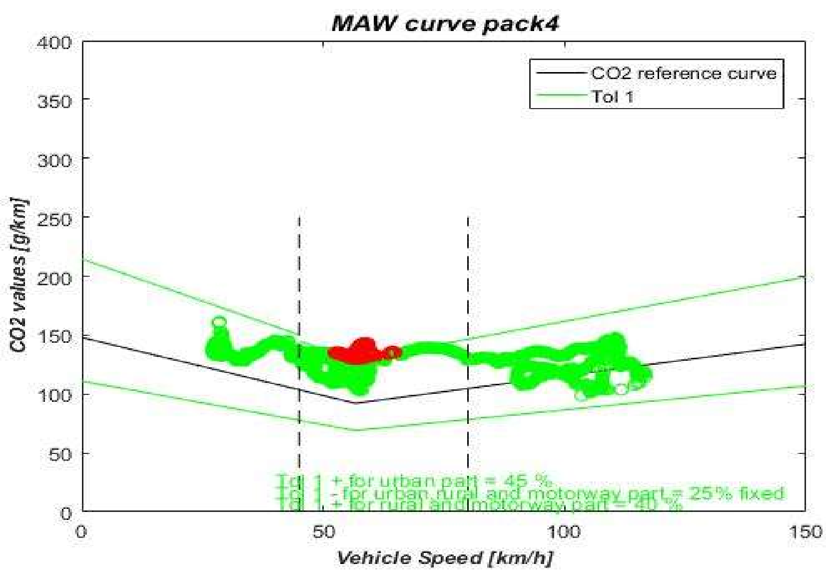


Figure 38 - Matlab routine - Emulation tool – RDE Pack 4 - MAW graphic - ID 213

MAW method will be used only to validate the trip, because in NOx emissions evaluation it will be replaced by the calculation of the total mass of pollutant emitted divided for the total distance travelled and multiplied for an evaluation factor which depends on CO_{2RDE}/CO_{2WLTP} to take into account the CO_2 produced during an RDE test.
In this way two RDE tests which have been driven in a different way (less or more aggressive), are standardized and normalized in the NOx evaluation.
In the RDE tests taken in exam only NOx raw urban emissions in ID 58 have been corrected because for the other tests the ratio $CO_{2,RDE}/CO_{2,WLTP}$ is lower than 1.30 (RFL1 considering the final version of RDE pack 4) and so the evaluation factor is set to 1 (see the graphic below).

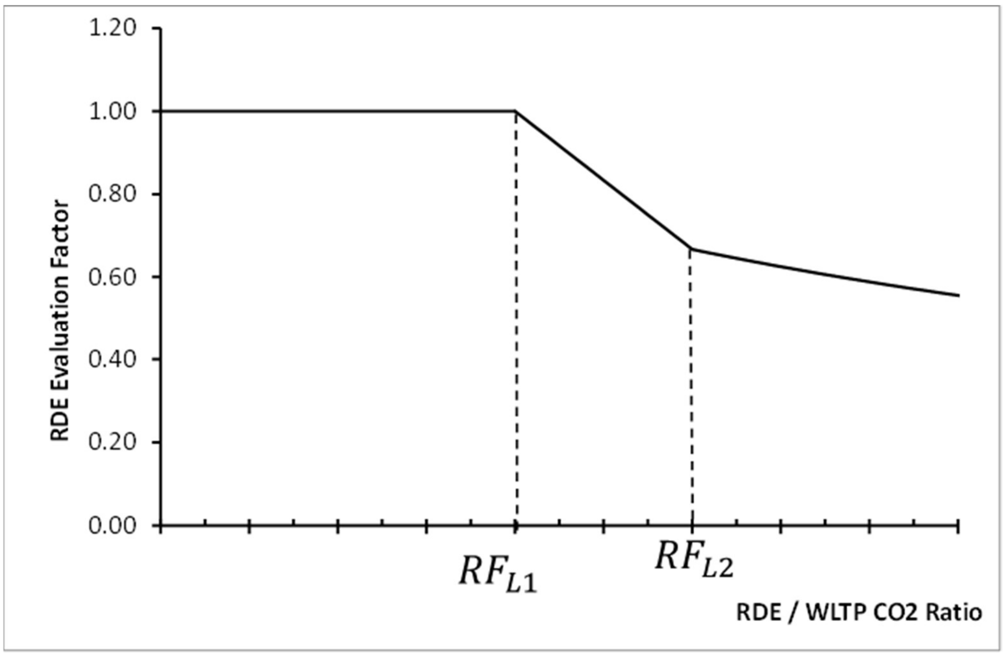


Figure 39 - Matlab routine - Emulation tool – RDE Pack 4 -Evaluation factor

Parameter	Unit	ID 58	ID 61	ID 213
Total Evaluation Factor	-	1	1	1
Urban Evaluation Factor	-	0.9313	1	1
NOx Total Emissions	mg/km	60.83	22.55	41.84
NOx Urban Emissions	mg/km	51.03	27.63	44.73

Table 42 - Matlab routine - Emulation tool – RDE Pack 4 - NOx Emissions results

Conclusion

A Matlab routine has been developed to emulate the PEMS during an RDE test according to regulation (EC) 2017/1151.
After being validated in the previous chapter using the same input information as Horiba and Emroad software, it is changed in order to acquire information only from the ECU in order to post process an RDE test without the need of the PEMS.
In order to make it usable with different cars and different PC, a Matlab application has been created based on the matlab routine: it postprocesses INCA data according RDE Pack 3 and Pack 4 for ICE and HEV.
It produces a report (.txt) with all the parameters considered by the regulation and some graphics (vehicle speed related to time, road gradient and discrete altitude related to test distance, vapos [95] and RPA graphics and MAW graphics according to RDE Pack 3 and 4).

The comparison between the results obtained postprocessing PEMS data and ECU data (different input information) raises the following problems:

- Small imprecision in the evaluation of parameters at high speed (i.e. motorway distance, vapos [95] and RPA in the motorway part of the test) due to the discrepancy between GPS and ECU vehicle speed;

- Small imprecision in Power Binning results: it has not been investigated deeply because this method will disappear in RDE Pack 4 from 2019;

- Small difference in the evaluation of CO_2 emissions due to small imprecision in PEMS analyzer measurement. In fact the formula based on fuel quantity demand gives very similar results to VEL bags measurements;

- High difference in the evaluation of NOx emissions due to errors in NOx estimator and sensor analysis. The PEMS analyzer gives very similar results to VEL tailpipe measurements as the NOx sensor and estimator analysis presents two problems: underestimation of NOx emissions in the first part of the trip where the sensor is not working and lack of separation in sensor measurement between NOx and NH_3.
  These problems can be reduced thanks to the technological development of the NOx estimator and sensor (in the Honda T113 the newest sensor is not mounted) and with the usage of a NH_3 sensor which can detect the presence of ammonia slip.

NOx instantaneous analysis in the Honda T 113

Introduction

In the last part of this thesis an analysis of instantaneous NOx emissions of a tested vehicle is done in order to understand and define which are the worst conditions which increases NOx production in a diesel internal combustion engine.
Nowadays researches and studies in the vehicle emissions field are focused on this kind of pollutant because of its high danger for human health even if the main contribute to the global level of NOx in the air is due to the heating systems in houses and industries.
The most dangerous oxide is NO_2 but because of the ease to oxidize NO in NO_2 these two chemical species are considered together in the regulation.
These pollutants cause problems for airways (irritations, chronic inflammations, reduction of pulmonary functions), hearth and eyes.

NOx analysis is really important in diesel engines because of the presence of thermal and gas conditions which cause its formation (high temperature and high presence of O_2) and because of the absence of a stoichiometric mixture (diesel engine works in lean mixture) which doesn't allow the three way catalyst to work correctly and causes the need of different catalytic systems to reduce it.
For this reason in diesel engine three possible different after treatment systems can be used:

- LNT: system characterized by the presence of barium carbonate which adsorb NOx in the normal working (lean mixture) to transform it into barium nitrate and release it after post – injections (rich mixture) to let NOx to be reduced in N_2 giving out their oxygen; this second part of the process is defined as LNT regeneration and it happens frequently but for few seconds.
  The main problem of this system is that it is characterized by a high efficiency only in a small temperature interval.
- SCR : system characterized by injection of Adblue (35% of urea in water) which, towards hydrolysis, produces NH_3 which reacts with NOx reducing them in N_2.
  This system is characterized by a high efficiency in a bigger temperature interval but for low temperatures it highly decreases.
- SDPF : system used to reduce NOx towards the injection of urea (as the SCR) and to oxidate particulate towards the gateway to channels alternatively closed to the extreme (as the DPF). It allows to reduce the clearances and for this reason it can be positioned close-coupled (near the engine) in order to warm up sooner.

The last benchmark activity about the NOx catalysts present in the actual vehicles shows the need of having at least two NOx reducers in order to achieve NOx limits defined in the regulation (80 mg/km for diesel engines). This is the case of the vehicle tested during my experience in "Delphi Technologies" as it is presented in the following chapter.

Test Vehicle – Honda T 113

The vehicle taken in exam is an Honda T 113.

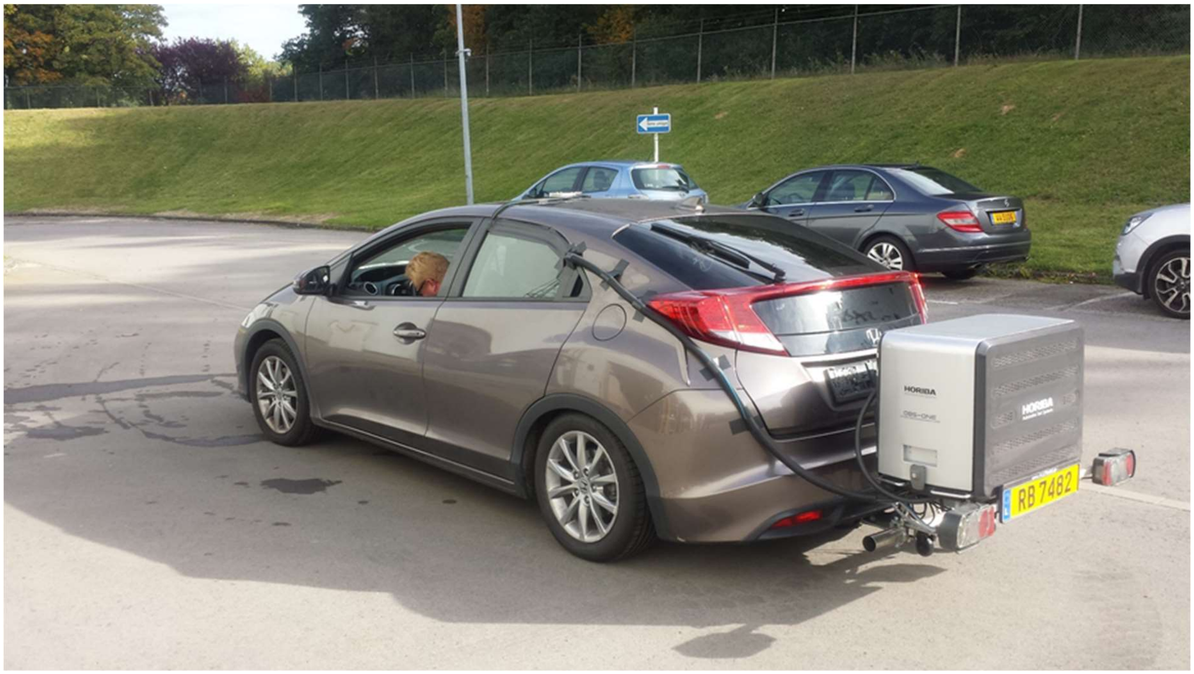


Figure 40 – NOx analysis – Honda T 113

It has the following characteristics:

- Engine definition:
    - In-line 4 cylinders engine
    - 16 valves
    - Engine capacity = 1.6 l
    - HP & LP EGR

- FIE definition:
    - 2000 bar rail pressure;
    - Pump Delphi DFP 6.1E
    - Injector: DFI 1.20
    - ECU: DCM 6.2

- After treatment definition:
    - DOC
    - Close-couple SDPF
    - Under floor SCR

For my purpose it is interesting analyzing deeply the after treatment system which is present and the reasons of the position of each catalyzer in the exhaust line.

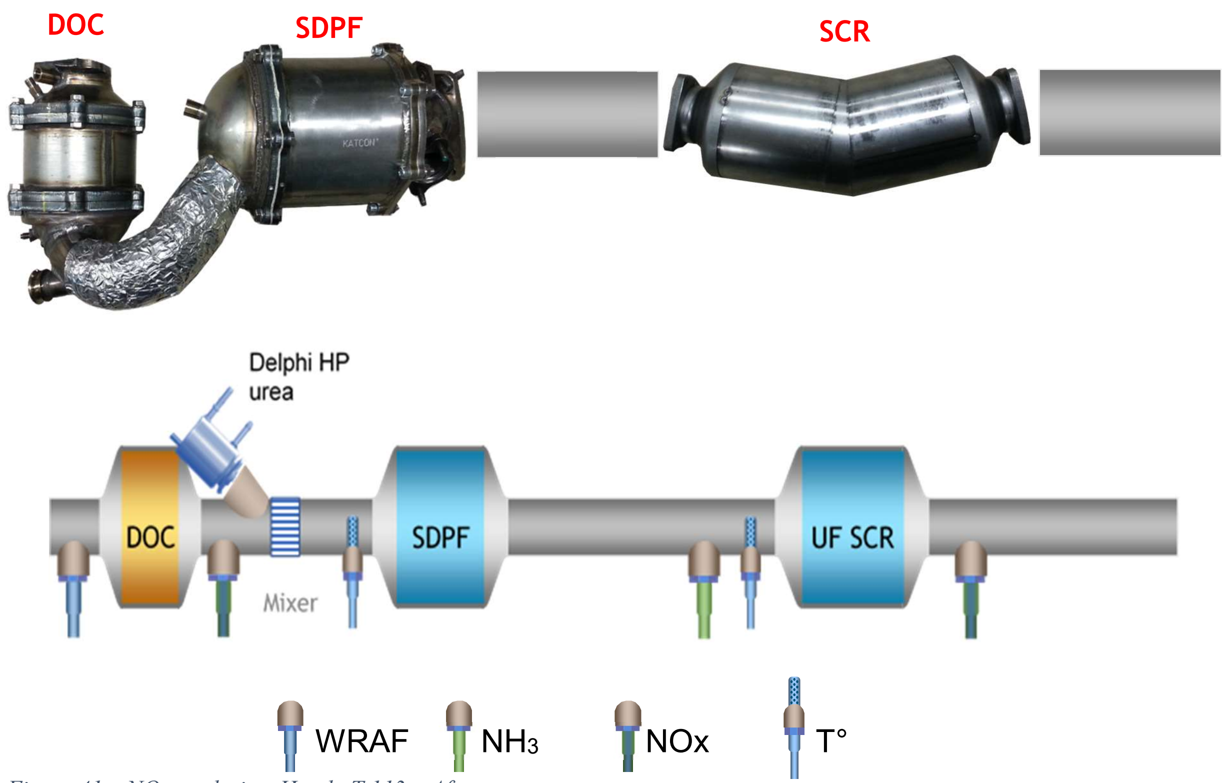


Figure 41 – NOx analysis – Honda T 113 – After-treatment system

First of all a DOC is present: it is used to oxidase CO and HC and it is close to the engine because it needs high temperatures to work with high efficiency.
Secondly there is an SDPF preceded by an urea injector and a mixer: it is in close-couple position because DPF needs high temperature to oxidase the particulate efficiently and to let the SCR to reach the light – off temperature to reduce NOx (200 - 250 degC) sooner than the under floor SCR.
Finally a second SCR is placed under floor in order to guarantee an high NOx efficiency at high load because it reaches a lower temperature than the first SCR avoiding the decaying of NOx efficiency at very high temperatures (see the graphic below).
To sum up the first SCR is fundamental to reduce NOx at the beginning of the test while the catalyzer system needs to warm up and the second SCR is very important when loads and temperatures become higher and the efficiency of the first SCR starts to decrease.
In the scheme above, the sensors used for the following NOx analysis are set out: there are two NOx sensors which measures NOx engine-out (after DOC) and tailpipe (after the underfloor SCR), two sensors which measures SDPF and SCR temperature, one which measures NH_3 at the entrance of the second SCR and a wide range air fuel sensor to measure the air fuel ratio of the exhaust.

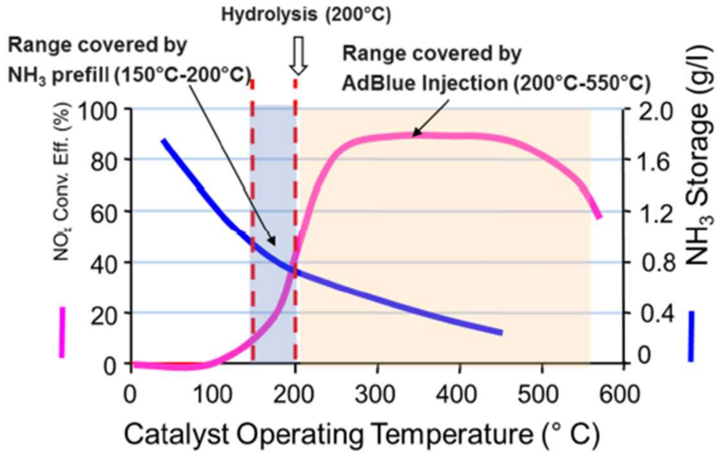
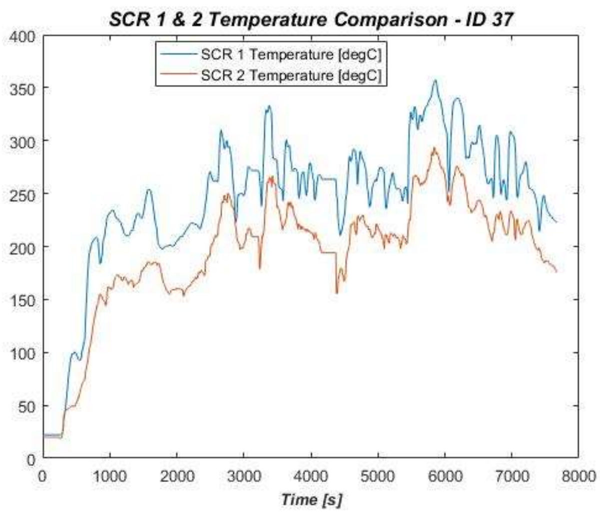


Figure 42 – NOx analysis – SCR NOx conversion efficiency vs SCR Temperature



ID 37

The SDPF (SCR 1) reaches 250 degC after 1600 seconds as the SCR 2 reaches it after 2700 seconds: SDPF fundamental at the beginning of the test.

Maximum SDPF temperature about 350 degC: no efficiency decay.

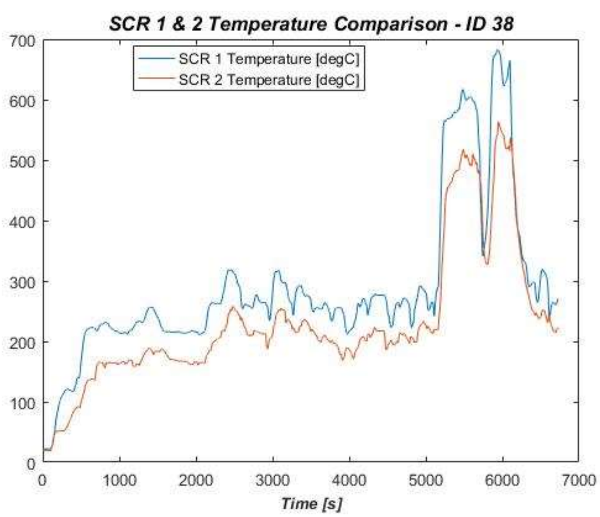


Figure 43 – NOx analysis – SCR 1 & 2 Temperature – Example ID 38

ID 38

The SDPF (SCR 1) reaches 250 degC after 1400 seconds as the SCR 2 reaches it after 2400 seconds: SDPF fundamental at the beginning of the test.

Maximum SDPF T about 700 degC: its efficiency decays.
Maximum SCR 2 T about 500 degC: its efficiency decays less.
SCR 2 fundamental at the end of the test.

NOx analysis

In this last chapter of my thesis instantaneous and cumulative NOx emissions have been analyzed for different tests driven with the Honda T 113.

Three types of test have been done:

- *<u>RDE test</u>*: trips driven in the real traffic and emissions measured by the PEMS following RDE regulation to look for different phenomena which increase NOx emissions (wavy driving style, DPF regeneration, cold/hot start) (ID 37, 38, 56, 57 & 221);
- *<u>NOx severity test</u>*: trip driven in the real traffic and emission measured by the PEMS without following the RDE regulation but to study trip conditions that are severe for NOx emissions (hill and downhill) and particular driving styles (ID 62 & 220);
- *<u>WLTC test</u>*: trip driven in a controlled area (windtunnel) and emissions measured by the PEMS and by the laboratory equipment (tailpipe and bags) following the WLTC regulation to study the effect of the external temperature in NOx emissions (WLTC at -7 and 23 degC).

In the emissions analysis two questions shall be developed:

- *<u>Why is NOx produced by the engine?</u>* It is possible to answer to this question studying NOx emissions measured by a vehicle sensor positioned engine – out and investigating a lot of different ECU parameters (pedal position, indicated torque, vehicle speed, EGR rate, exhaust temperature, air fuel ratio, injection timing, injection pressure and multiple injections);
- *<u>Why is not NOx eliminated completely by the after treatment system?</u>* It is possible to answer to this question studying NOx emissions measured tailpipe by the PEMS or the vehicle sensor positioned tailpipe and investigating after treatment conditions which determines SDFP and SCR efficiency (temperature, NH_3 capacity, NH_3 stored, NH_3 used, gas space velocity, NO2/NOx ratio).

Test N°	ID 37	ID 38	ID 56	ID 57	ID 62
Vehicle	Honda T 113				
Test type	RDE	RDE	RDE	RDE	NOx severity trip
Date	07/09/2017	08/09/2017	27/10/2017	31/10/2017	20/11/2017

Test N°	WLTC -7 degC	WLTC 23 degC	ID 220	ID 221
Vehicle	Honda T 113			
Test type	WLTC	WLTC	NOx severity trip	RDE
Date	17/04/2018	18/04/2018	16/05/2018	17/05/2018

Table 43 – NOx analysis – Tests analyzed

In the following analysis, in RDE and NOx severity trips, NOx engine – out emissions have been measured by a NOx sensor and NOx tailpipe emissions have been measured by the PEMS analyzer (more precise than the vehicle sensor present tailpipe).
In the WLTC tests both emissions have been measured by the laboratory equipment (more reliable than the PEMS analyzer).

External temperature effects in NOx emissions: comparison between WLTC at -7 and 23 degC

In order to analyze the effects of external temperature in NOx emissions two WLTC tests have been driven in the Windtunnel at -7 degC and 23 degC.
First of all the NOx engine – out analysis shall be done: it is expected that, all test conditions being equal, NOx produced by the engine in the cold WLTC are lower than the one produced by the engine in the hot WLTC because higher external temperature should cause higher temperature in the combustion chamber which contribute to produce more NOx.

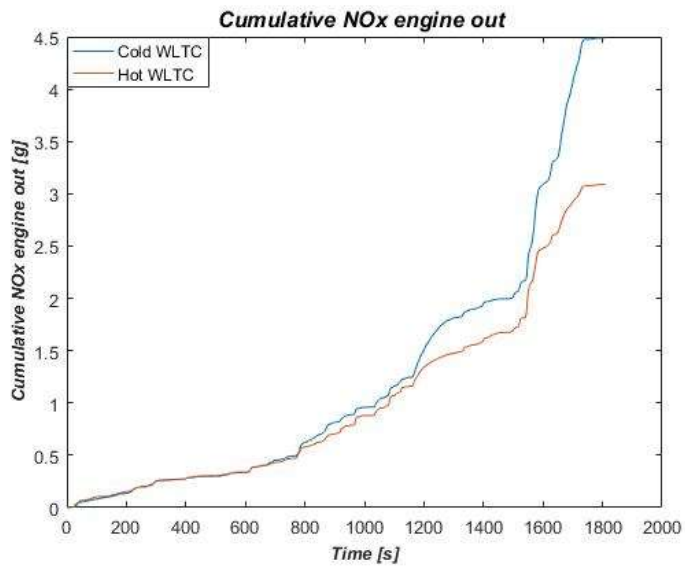


Figure 44 – NOx analysis – Ext T effects – NOx engine out [g]

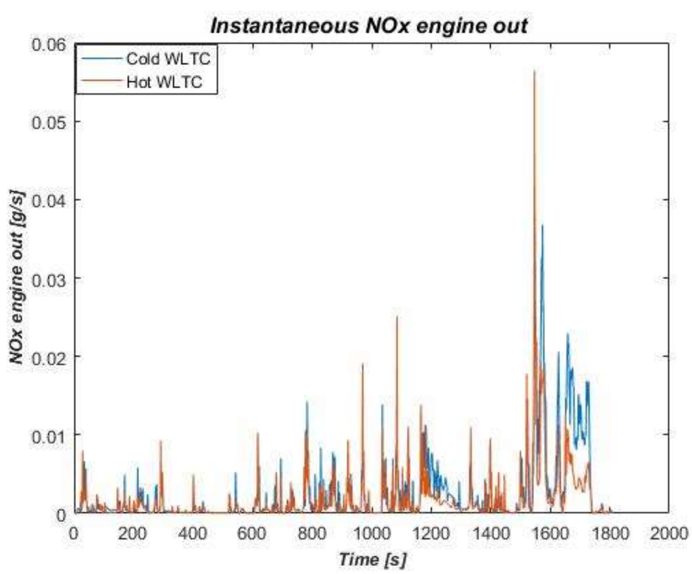


Figure 45 – NOx analysis – Ext T effects – NOx engine out [g/s]

As it is showed in the graphics above, this does not happen because all the test conditions are not equal but there are differences in driving style and ECU strategies:

- *Driving style*: EGR rate: in the cold test the EGR level is lower in particular during the time intervals [1200,1300] s and [1550,1750] s.
  A lower EGR level causes a lower quantity of recycled exhaust gas and so higher temperatures in the chamber with a consequent increase in NOx emissions.
  It has a high effect in this analysis because a small decrease in EGR rate causes a high variation in NOx emissions;

- *ECU strategy*: timing of the main injection: as it is shown in the graphic below, when the external temperature is lower, ECU anticipates the combustion to be sure that it finishes completely even if external condition are more severe.
  Because of this phenomena, premixed combustion lasts more time and so temperature and pressure in the chamber are higher than the case of hot test: this cause an increase in NOx emitted engine – out.
  It has a small effect in this analysis because high variations in the main injection timing (4 – 5 deg) cause small variations in NOx emissions.

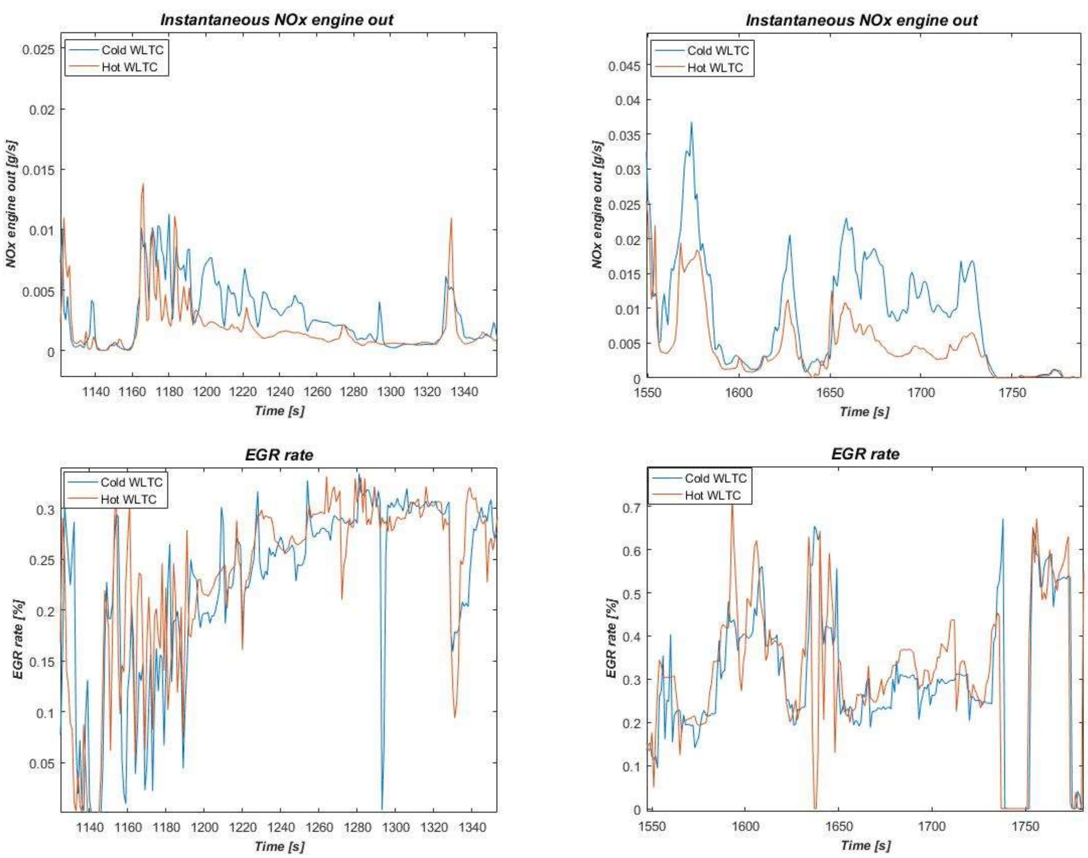


Figure 46 - NOx analysis – Ext T effects – EGR rate & Inst NOx

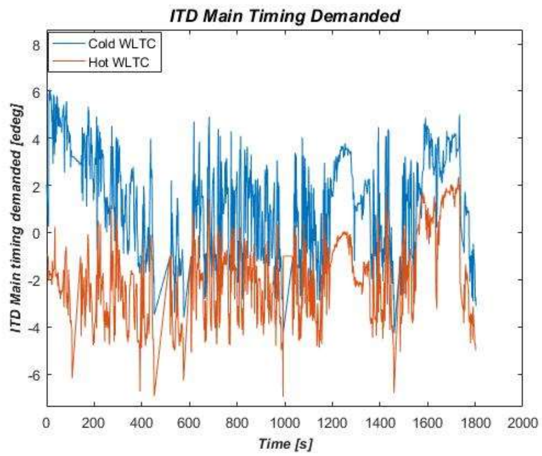


Figure 47 – NOx analysis – Ext T effects – Main injection timing

Considering NOx emissions measured tailpipe, no huge variations are noticed in instantaneous and cumulative evaluation (always 30% more of cold test NOx emissions than hot test) due to very similar NOx conversion efficiency:

- η_{COLD} = 0.644
- η_{HOT} = 0.650

In which the efficiency is calculated as $\eta = 1 - \frac{NOx\ TAILPIPE\_VEL}{NOx\ ENG\ OUT\_VEL}$

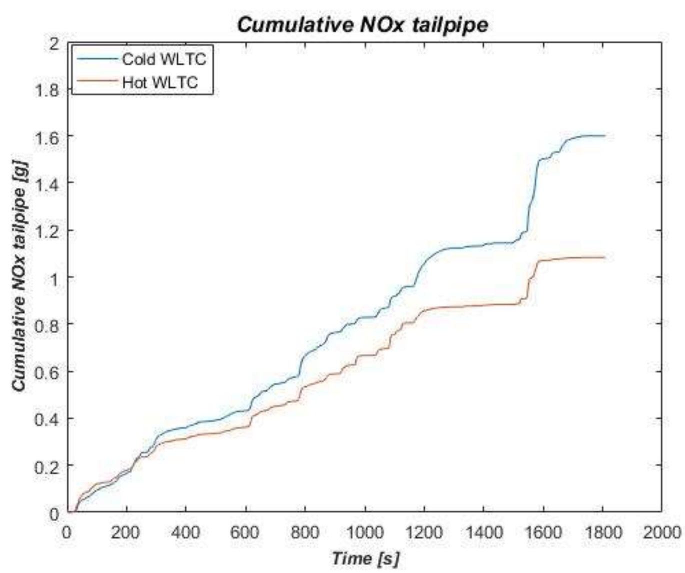


Figure 48 – NOx analysis – Ext T effects –NOx tailpipe [g]

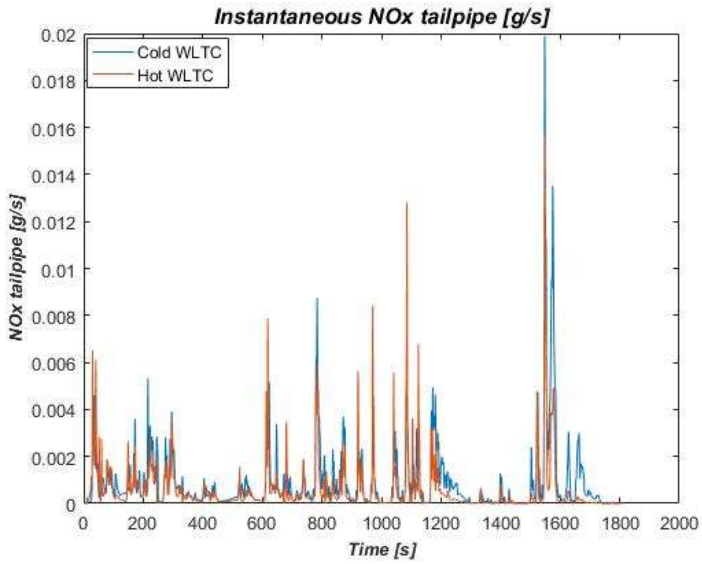


Figure 49 – NOx analysis – Ext T effects –NOx tailpipe [g/s]

It happens because the SCR temperature is slightly lower in the cold test but its small effects are compensated by a much higher quantity of NH3 used (also caused by higher engine – out NOx emissions and, so, higher need of reductant).

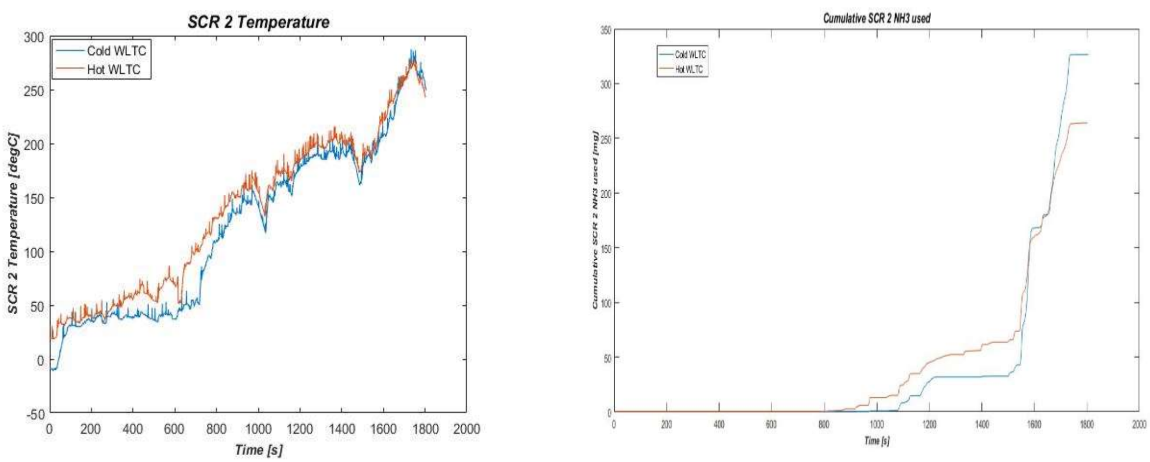


Figure 50 – NOx analysis – Ext T effects – SCR 2 Temperature & NH3 used

DPF Regeneration effects in NOx emissions: comparison between ID 37 and ID 38

The second analysis done in this study regards the effects in NOx emissions (measured engine – out and tailpipe) of a DPF regeneration.
In order to achieve this goal two test driven by the same person, in the same trip and with similar ambient conditions, but one with regeneration and one without, have been compared. First of all NOx engine – out emissions are analyzed: as it is expected, RDE test with DPF regeneration produces more NOx than the other test because EGR is completely cut during it. HP EGR is cut to let the hydrocarbons, which are produced with post – injections, not to come back at the intake but to reach the DOC in order to increase its and, consequently, DPF temperature. LP EGR is cut to avoid a further increase of exhaust temperature (already high because of the presence of DPF regeneration).
If the EGR is lower, NOx emissions are higher because of lack of recycled exhaust gas which would have decreased combustion temperature and, so, NOx production.
In the figures below it shall be noticed that the sensor is not working for the first 500 seconds of the test because it needs a warm-up period.

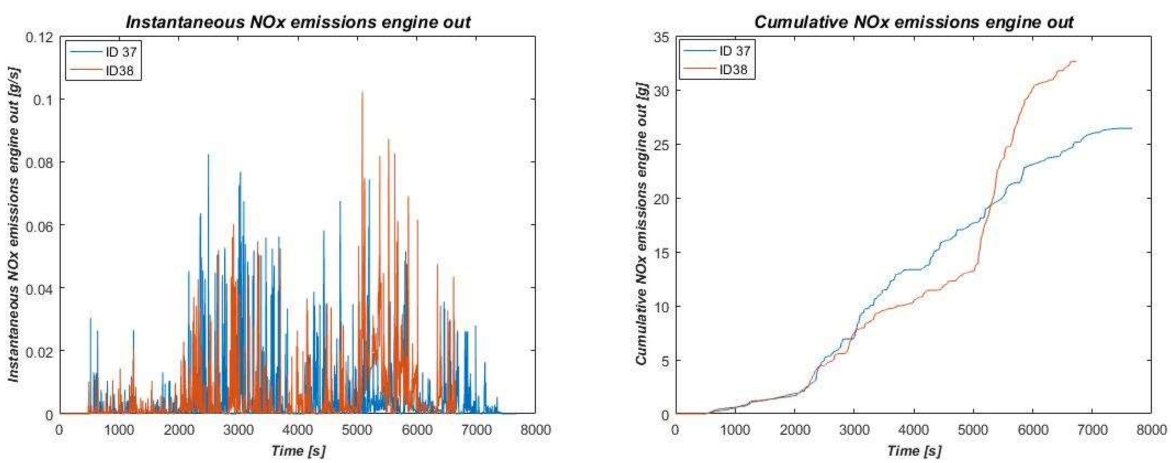


Figure 51 – NOx analysis – DPF regen effects –NOx engine out [g/s] & [g]

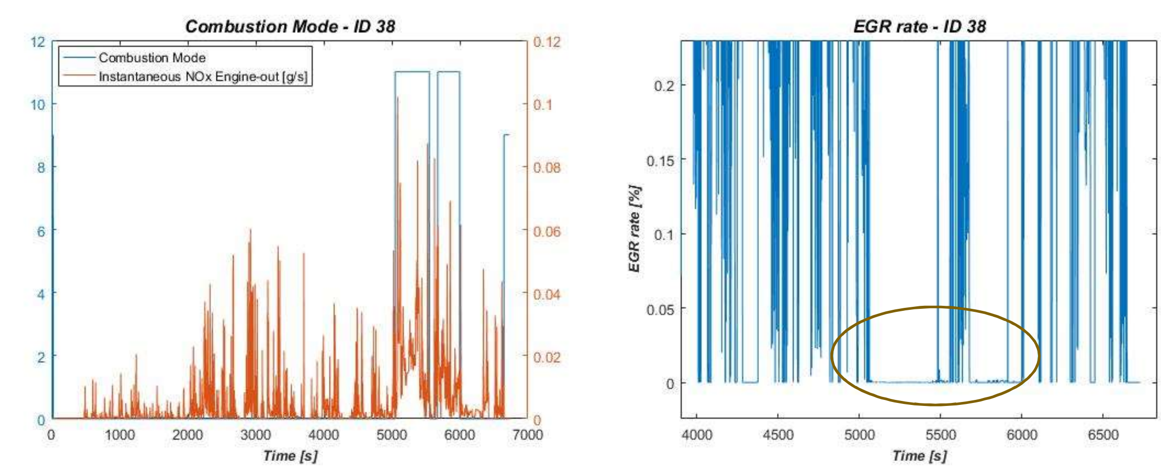


Figure 52 – NOx analysis – DPF regen effects – Combustion mode & EGR rate

Secondly, analyzing NOx emissions measured tailpipe, a high increase in the difference between the two tests is founded (19 % engine-out and 65 % tailpipe) due to a high difference in NOx conversion efficiency during the total trip:

- η ID37 = 0.877
- η ID38 = 0.719

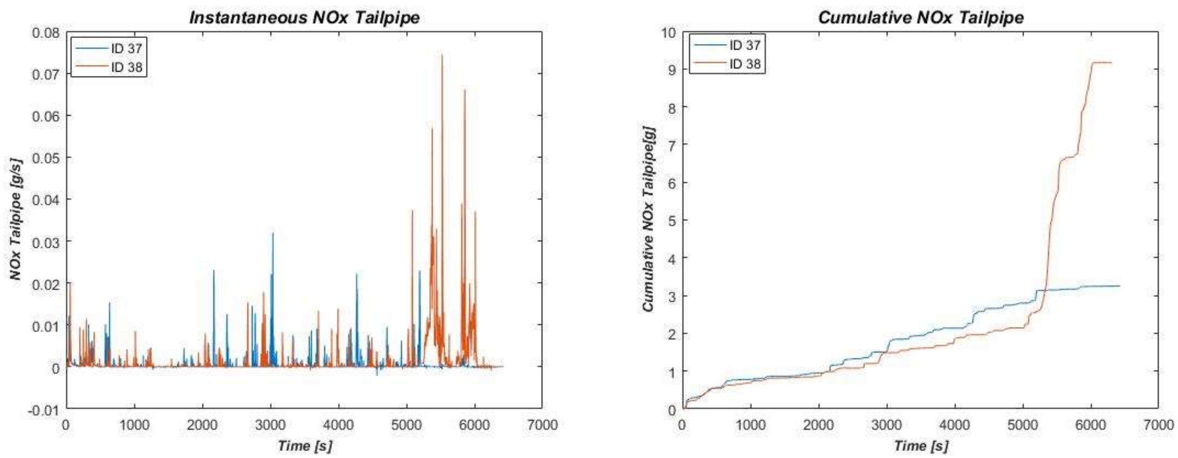


Figure 53 – NOx analysis – DPF regen effects – NOx tailpipe [g/s] & [g]

This happens because, in ID 38, after treatment system doesn't work in the proper way at high catalyzer temperatures reached during the DPF regeneration (high catalyzer temperatures are needed to eliminate all the particulate from the DPF).
The SDPF and the SCR positioned close coupled reach high temperature and this cause a decrease of their NH_3 capacity (in particular regarding the second SCR which is the most involved in the deterioration of its efficiency). Because of the decrease of the capacity, the NH_3 stored in the two SCR highly is reduced and it causes an high decline of their conversion efficiency (as it is showed in the graphic below which compares conversion efficiency with NH_3 stored).

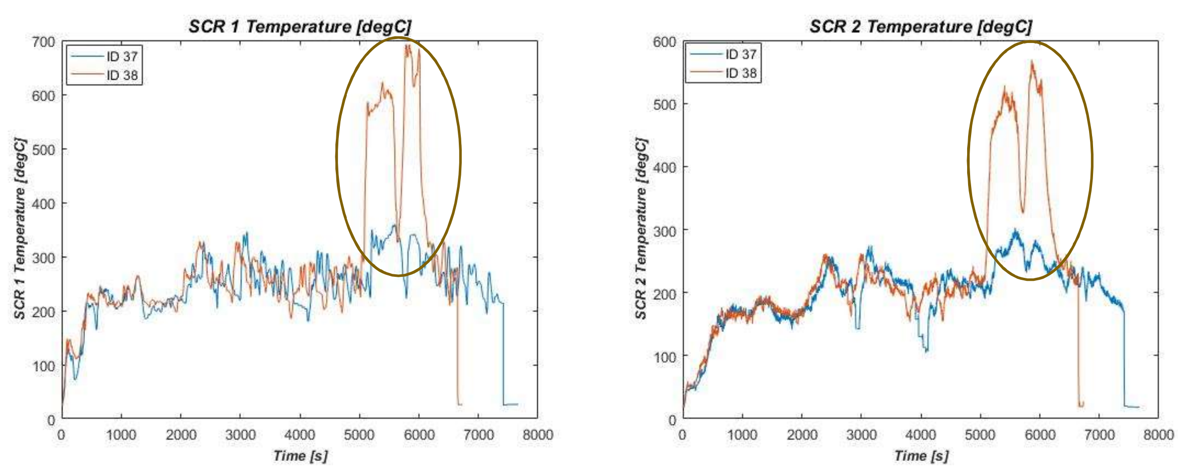


Figure 54 – NOx analysis – DPF regen effects – SCR 1 & 2 Temperature

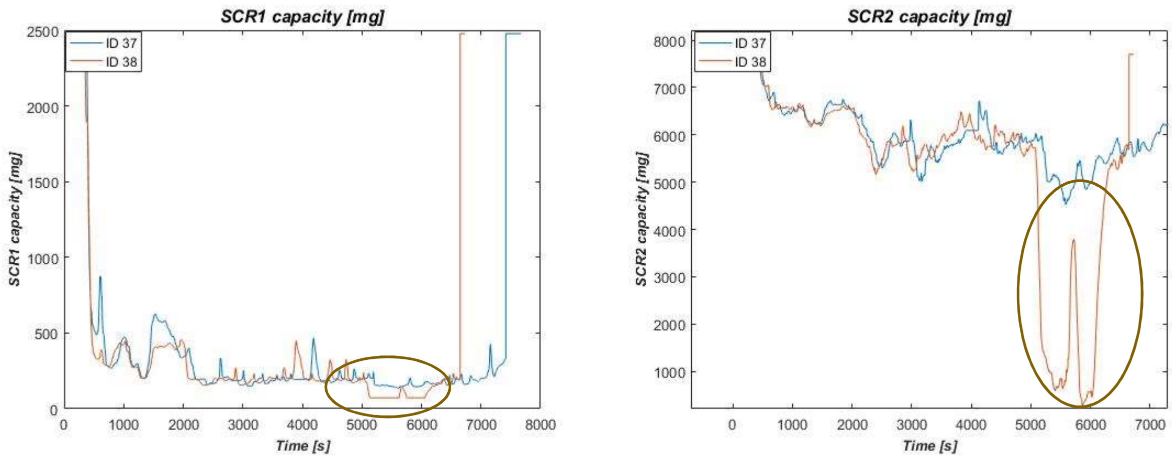


Figure 55 – NOx analysis – DPF regen effects – SCR 1 & 2 capacity

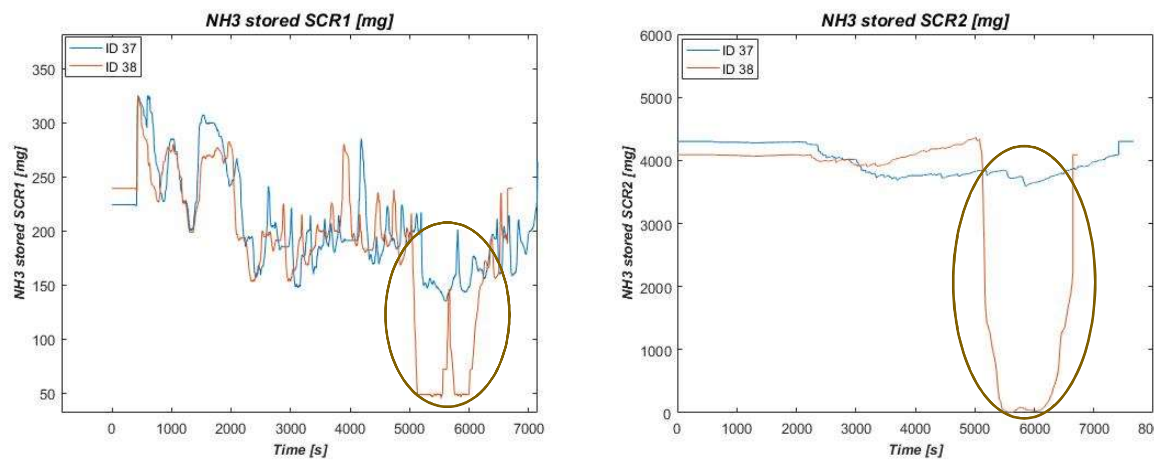


Figure 56 – NOx analysis – DPF regen effects – NH_3 stored

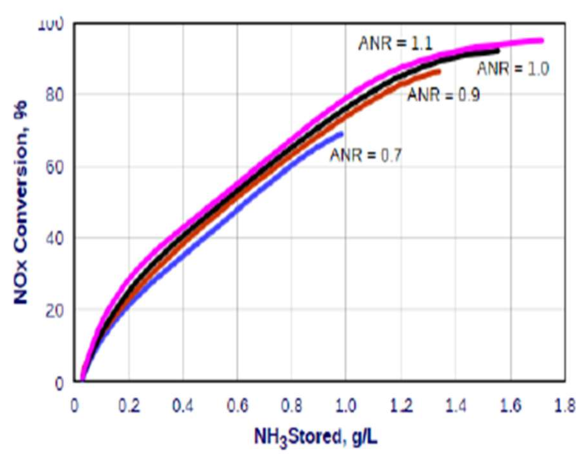


Figure 57 – NOx analysis – DPF regen effects – SCR NOx conv. eff. vs SCR NH_3 stored

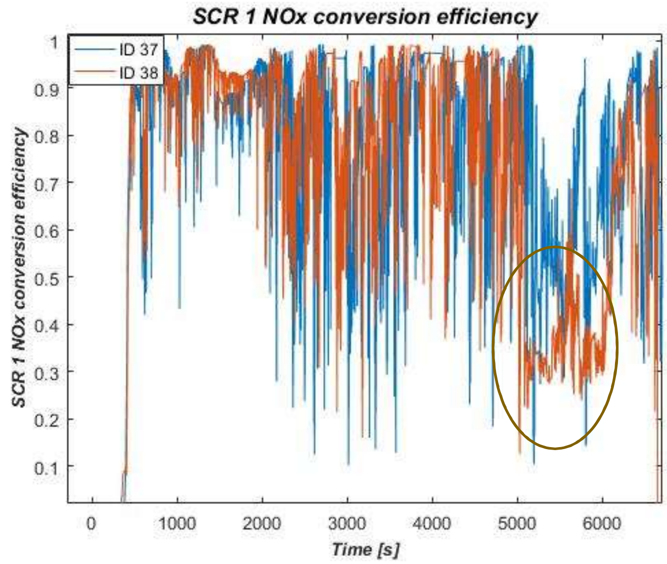


Figure 58 – NOx analysis – DPF regen effects – SCR 1 NOx conversion efficiency

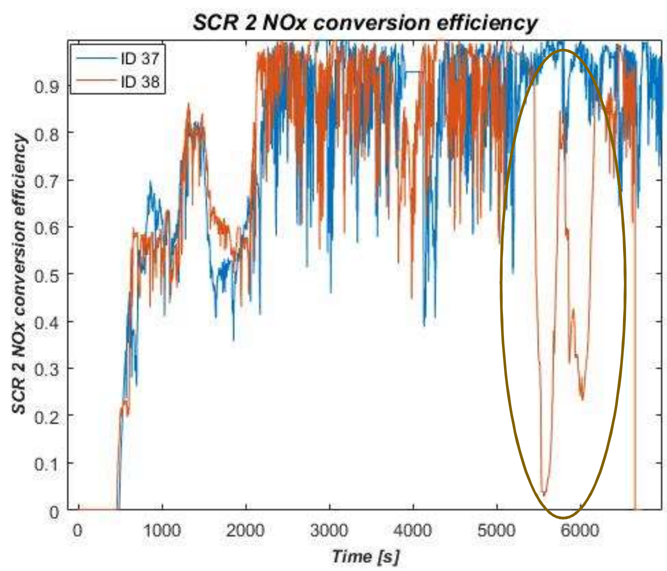


Figure 59 – NOx analysis – DPF regen effects – SCR 2 NOx conversion efficiency

Cold start effects in NOx emissions: comparison between ID 37 and ID 221

In order to analyze the effects of cold start in NOx emissions, two tests with the same trip but different driver and test start recording have been compared.

ID 37 has been characterized by a cold start: data recording started before engine has been switched on after more than one day of soaking in the garage at 23 degC as in ID 221 data started to be recorded after the warm-up of the car (in particular after coolant temperature reaches 90 degC).

First of all it can be noticed that engine-out emissions can not be compared for the first 500 seconds of the tests because of differences in sensors working (in ID 37 the sensor is not working because it is cold as in ID 221 it is working properly since the first second of the test) and, so, cold start effects can be studied only considering tailpipe emissions (measured by PEMS analyzer which works properly during all the RDE test).

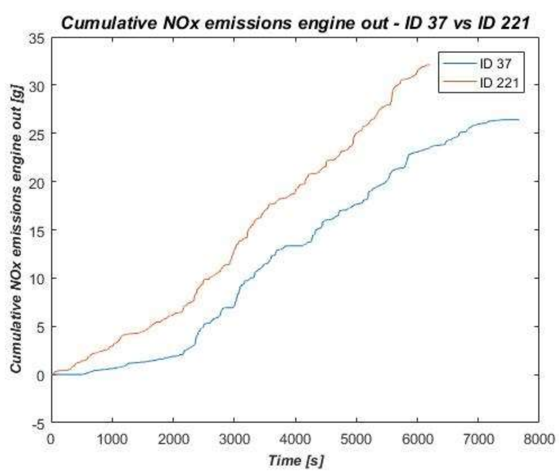


Figure 60 – NOx analysis – Cold start effects – NOx engine out [g]

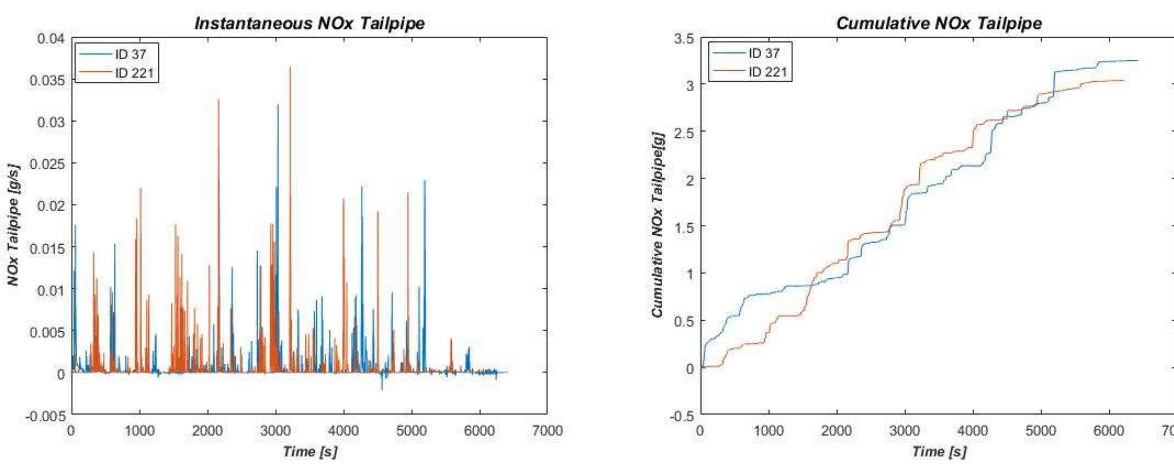


Figure 61 – NOx analysis – Cold start effects –NOx tailpipe [g/s] & [g]

Comparing the engine coolant temperature it can be noticed that the cold start period in ID 37 lasts about 1000 seconds.

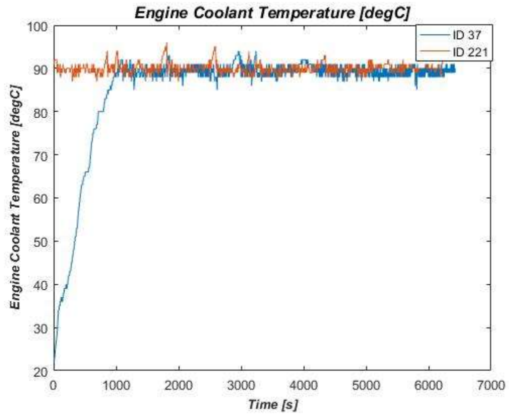


Figure 62 – NOx analysis – Cold start effects – Engine coolant temperature

In this time interval it can be noticed that NOx emissions measured tailpipe are higher in the cold start test than to the hot start test because of higher catalyzer temperature and, so, higher NOx conversion efficiency (SCR 2 close couple, in the cold start test, needs 1300 seconds to reach 200 degC, the minimum temperature which lets good NOx conversion efficiency).

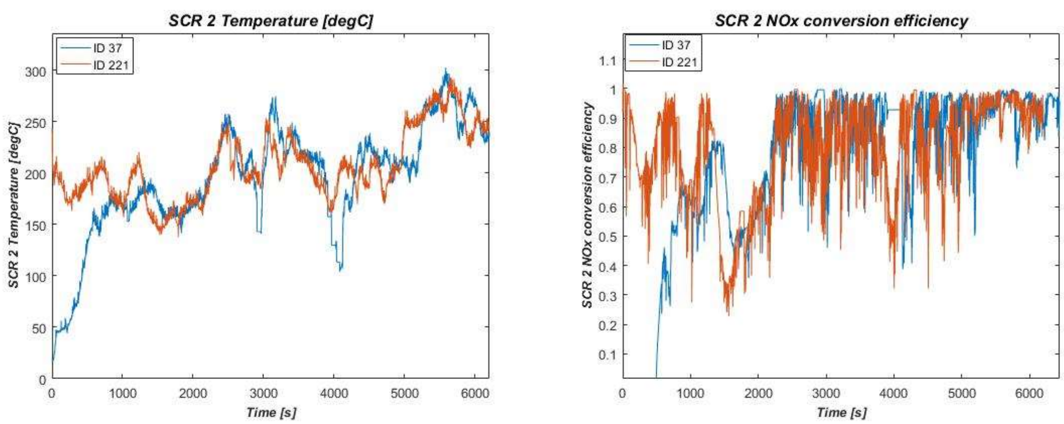


Figure 63 – NOx analysis – Cold start effects – SCR 2 Temperature & NOx conv. eff.

Despite this effect of the cold start, NOx emissions measured in the urban part in ID 221 are higher than ID 37: this happens thanks to two steps present at about 1000 and 1600 seconds after the start of the test (as it is shown in the cumulative NOx tailpipe graphic).
The main cause of this phenomena is the different driving style between the two tests as it will be explained in the following chapter.
Instead, the SCR behaviour is quite similar (graphic above of SCR 2 Temperature and efficiency) : this explains why, considering NOx engine-out and tailpipe emissions from 600 seconds to the end of the acquisition, the difference between the two different RDE tests is quite similar in percentage: so, the difference between the tailpipe NOx emissions in the two tests derived mainly from different NOx engine-out emissions.

Different driving style

The two tests that have been compared were driven by two different people: it causes a different driving style which can explain different NOx engine – out emissions.
In particular ID 221 has been driven in a more aggressive way: this can be justified by different parameters and it explained why NOx urban emissions in ID 221 are higher than in ID 37.
First of all, looking vapos [95] and RPA graphics, the orange points referred to ID 221 are positioned higher than grey points (ID 37) (even if both tests satisfy dynamics RDE requirements): this is a consequence of a bigger acceleration in the ID 221.

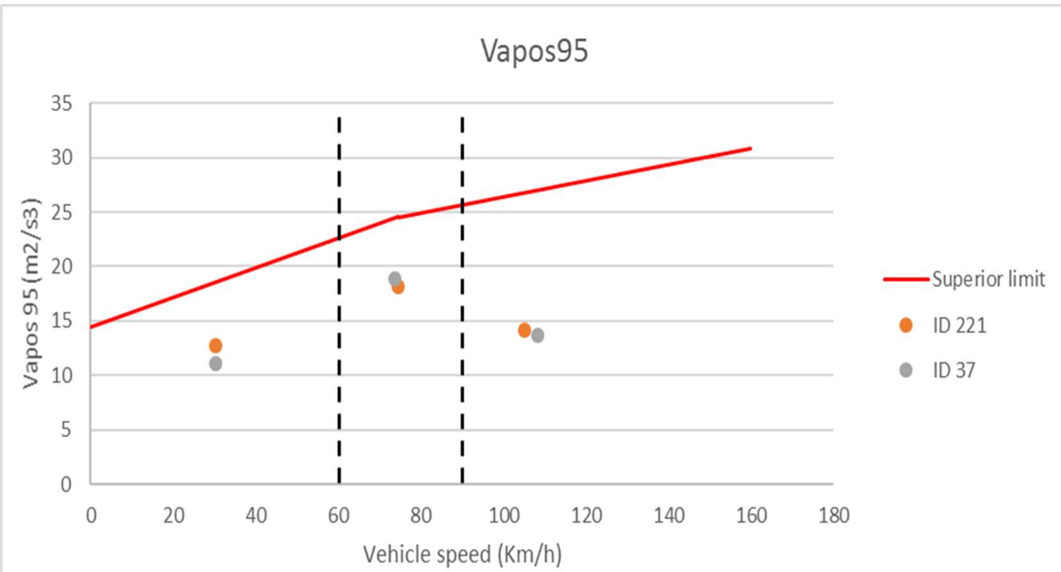


Figure 64 – NOx analysis – Cold start effects – vapos [95] graphic

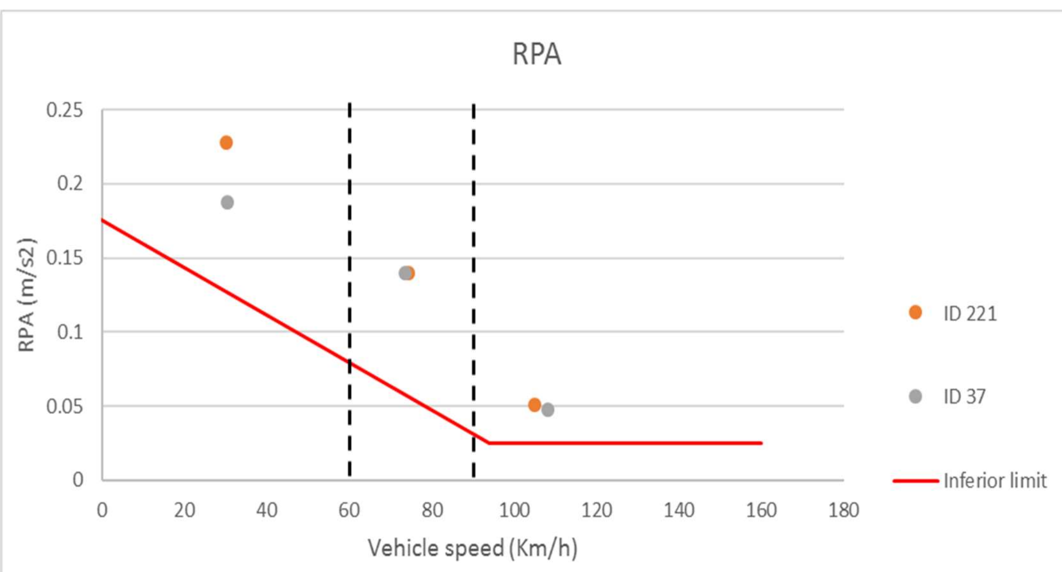


Figure 65 – NOx analysis – Cold start effects – RPA graphic

Secondly, in ID 221, the accelerator has been pushed more (in particular at about 1000 and 1600 seconds) and this explain why the indicated torque is higher than ID 37.
For this reason EGR rate in ID 221 is lower than ID 37 (at high load the engine is working with a smaller level of EGR to ensure high power).
This phenomena gives the main contribute to NOx emissions increase: with lower EGR rate, in fact, the temperature in the chamber is higher and, so, more NOx engine out are produced (and consequently more NOx tailpipe are emitted considering similar SCR behaviour).

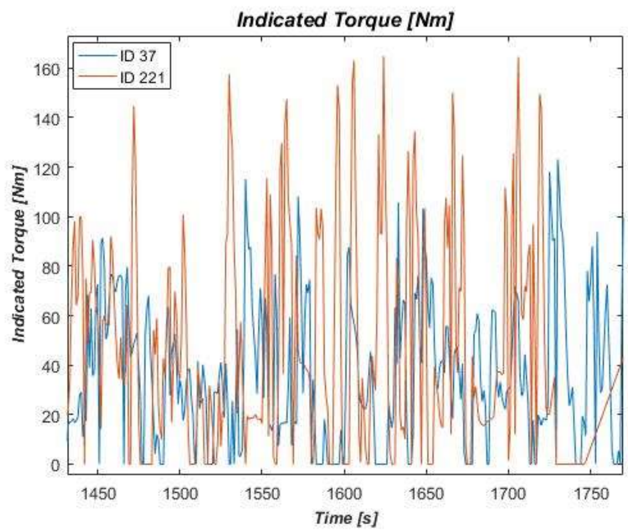


Figure 66 – NOx analysis – Cold start effects – Indicated torque

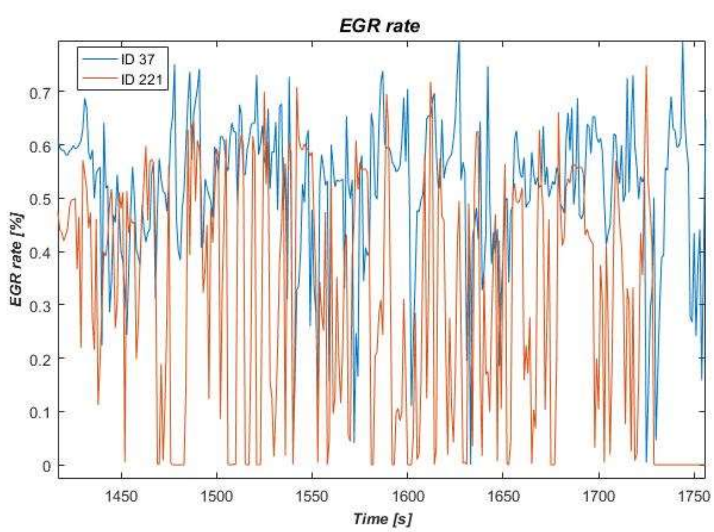


Figure 67 – NOx analysis – Cold start effects – EGR rate

In conclusion it can be assessed that the cold start is a source of NOx emissions production but its effect can be easily overcame by other sources of emissions which can happen during an RDE test such as a more aggressive driving style or a different behaviour of after treatment system.
This is not caused by the time length of the test (about 6500 seconds, six times the cold start length) because cold start effects are overcame even if only the urban part is considered (first 2000 seconds of the test, only two times the cold start length) as it is explained below.

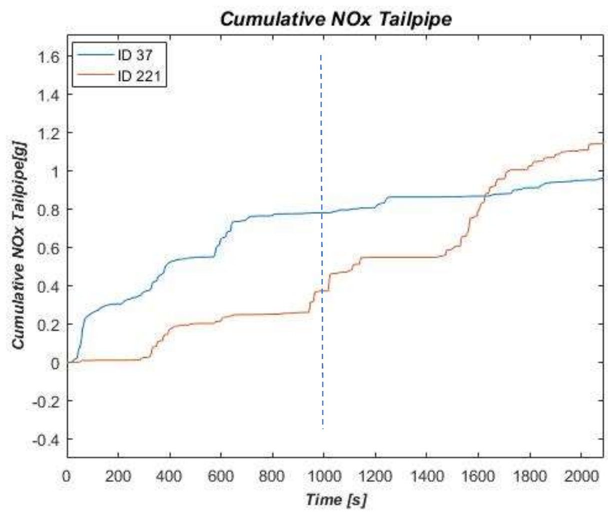


Figure 68 - NOx analysis – Cold start effects – NOx tailpipe [g]

	ID 37	ID 221	Absolute difference	% Difference
NOx tailpipe emissions at the end of the cold start (1000 s) [mg]	779.2	371.4	+ 407.8	+ 52 %
NOx tailpipe emissions at the end of the urban part (2000 s) [mg]	948.5	1106.2	- 157.7	- 17 %

Table 44 - NOx analysis – Cold start effects – Urban part results

Cold start causes NOx emission increase compared to hot start but its effect is recovered in the following 1000 seconds with a more aggressive driving style.
At the end of the urban part the hot start test taken in exam has produced more NOx than the cold start test.

Wavy driving style effects in NOx emissions: comparison between ID 56 and ID 57

As it has been introduced in the previous chapter an important point which has to be analyzed in NOx emissions evaluation is the driving style.

In this chapter a test driven with a common driving style (ID 56) is compared with a test characterized by a wavy driving style in the motorway part of the trip (ID 57) consisting in pushing and releasing accelerator frequently during the trip.

This particular way of driving increases transient periods during a test causing more production of NOx engine – out and reduction of SCR efficiency.

Starting from engine – out analysis an increase of 70 % of NOx emissions is present in ID 57 (wavy driving style) from 5350 seconds to the end of the test (motorway part).

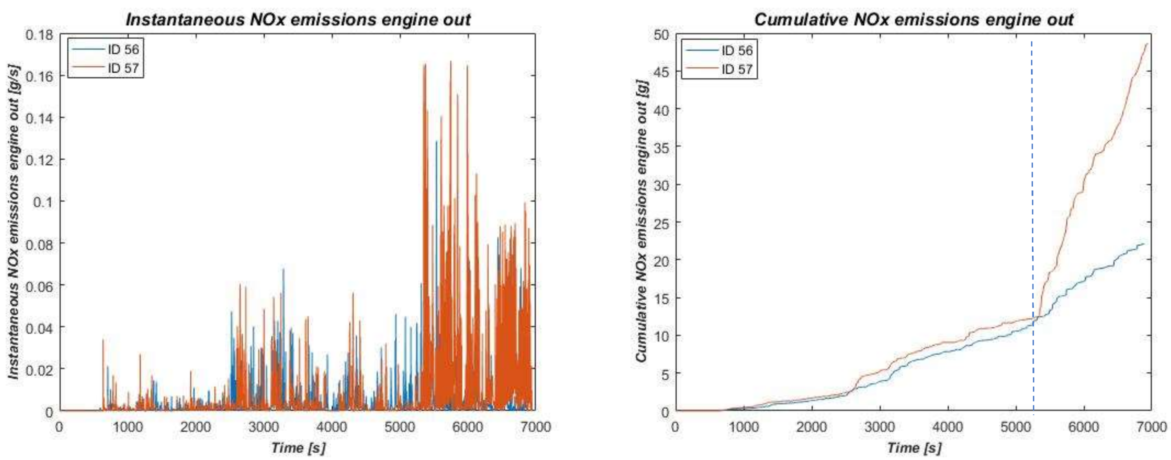


Figure 69 – NOx analysis – Wavy driving style effects –NOx engine out [g/s] & [g]

The presence of a particular driving style can be detected looking at vehicle speed, engine speed, indicated torque and pedal position records during the test.

It is evident as these parameters have an oscillating behaviour during ID 57 with a frequency of 0.2 Hz (period of 5 seconds).

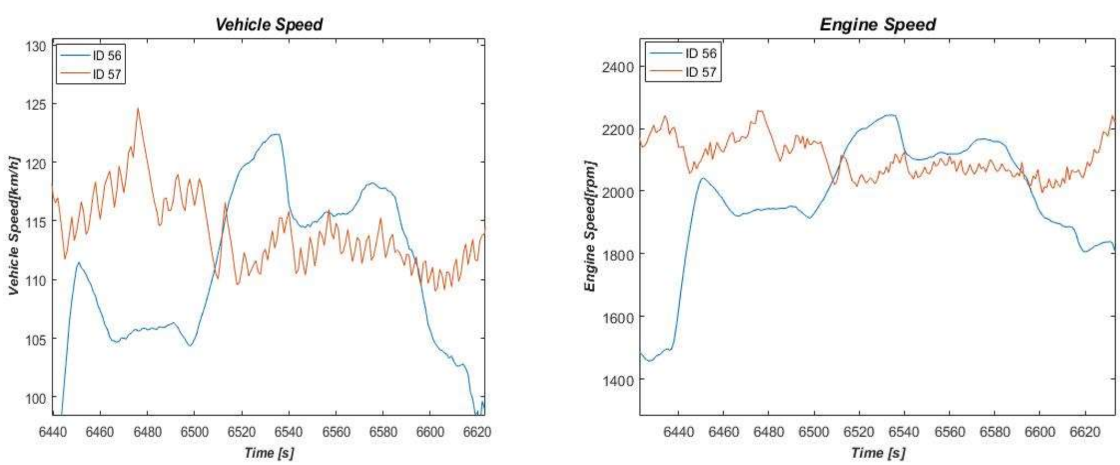


Figure 70 – NOx analysis – Wavy driving style effects – Vehicle & Engine speed

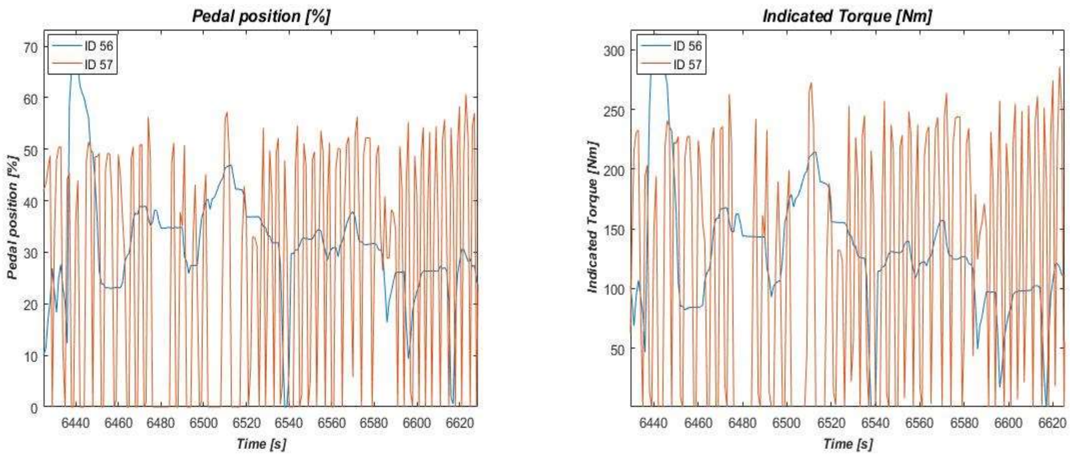


Figure 71 – NOx analysis – Wavy driving style effects – Pedal position & Indicated torque

This particular driving style causes a EGR rate reduction by the ECU for two reasons:

1. <u>Air fuel ratio limitation</u>: high EGR rate causes a richer mixture (because recirculated gas replace air): so, at high load when the mixture is closer to stoichiometric (less air is present), EGR is reduced not to get too richer and overpass the smoke limit;
2. <u>Turbolag limitation</u>: during transient the torque produced is not the one the driver is requesting because of delay in response time. So, to avoid, a further decrease of torque, EGR is cut during the beginning of the transient (because EGR is replacing fresh air and, so, is reducing the quantity of fuel which can be injected, causing a deterioration in engine indicated torque).

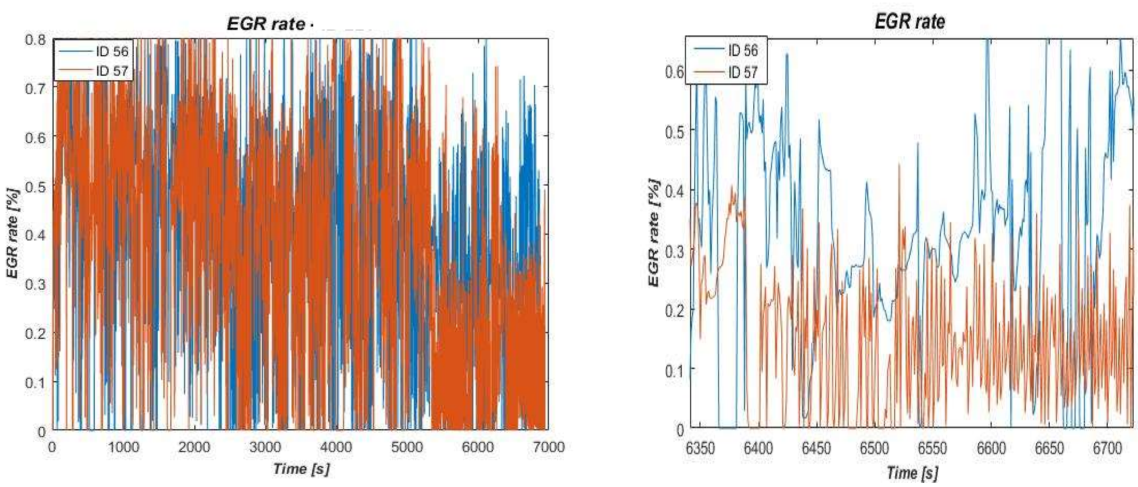


Figure 72 – NOx analysis – Wavy driving style effects – EGR rate

Secondly NOx tailpipe emissions can be studied in order to understand effects of this particular driving style on the catalyzer behaviour.

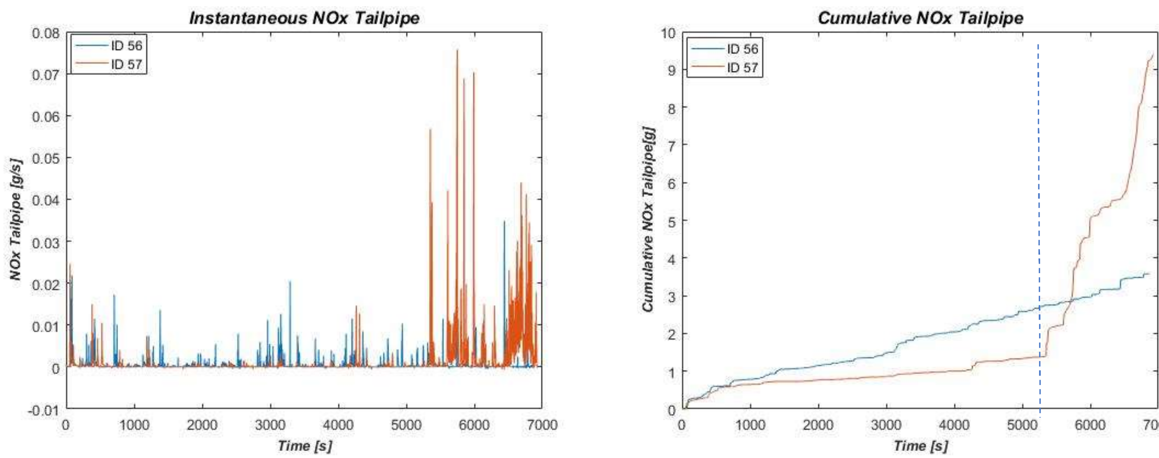


Figure 73 – NOx analysis – Wavy driving style effects – NOx tailpipe [g/s] & [g]

Studying NOx tailpipe emissions a difference of 90% has been found between two test in the same time interval detected before: this means that also the catalyzer behaviour has an impact on the increase of NOx emissions during a wavy driving style.

In fact, NOx conversion efficiency calculated considering only the interval characterized by a wavy driving style is much lower than the efficiency calculated for the normal driving test:

- η ID56 = 0.924
- η ID57 = 0.821

This is caused by the increasing of the exhaust mass flow which provokes an increase of the space velocity and, so, a decrease of the time spent by the exhaust gas in the catalyzer.

It is not caused by difference in SCR temperature because, as it is plotted below, they do not highly change between the two tests.

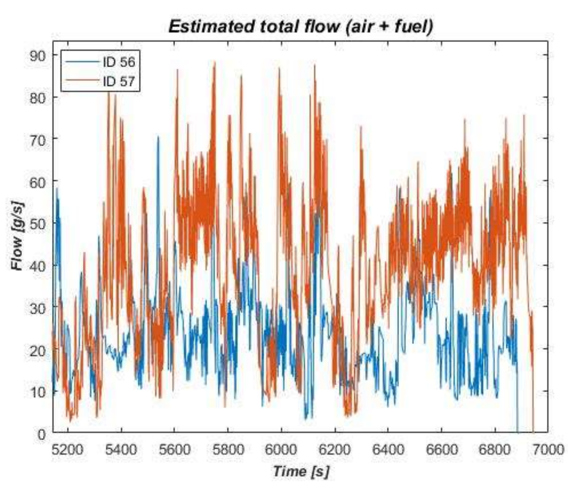


Figure 74 – NOx analysis – Wavy driving style effects – Estimated flow

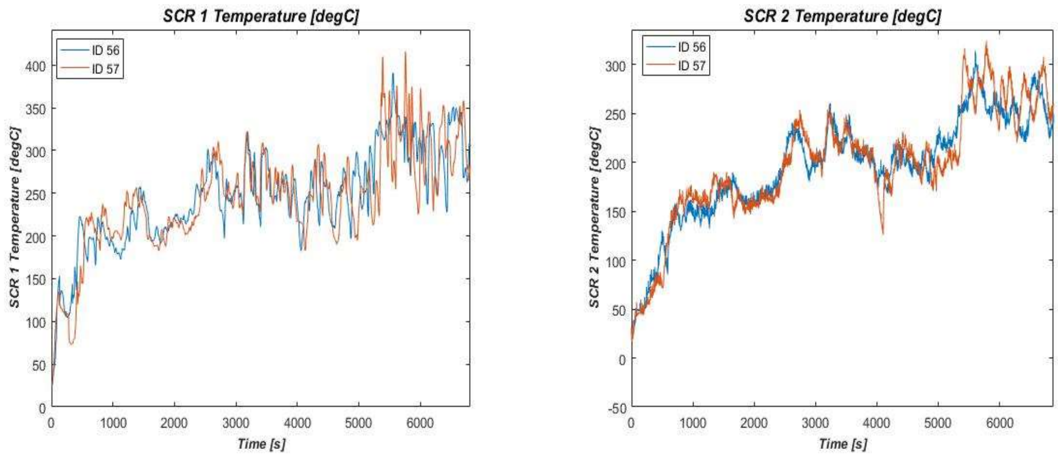


Figure 75 – NOx analysis – Wavy driving style effects – SCR 1 & 2 Temperature

In conclusion a wavy driving style causes an higher production of NOx engine – out because ECU cuts EGR at high load and during transient phases.
This effect is increased tailpipe because of the worse behaviour of catalyzers due to high exhaust flow needed to reach high load.
This analysis is important because this driving style is valid according to RDE regulation because no regulation limits have been exceeded.

Severe trips: effects in NOx emissions – Analysis of ID 62 and ID 220

In this last chapter about NOx instantaneous analysis two more severe trips for NOx emissions have been driven in order to investigate NOx production increase in particular roads characterized by consequent steep hills and downhills.
For this purpose no valid RDE test have been computed because of absence of distance covered in the motorway part but these small test parts could however be found in a valid unique RDE.
In the following pages a deeply analysis of emissions during these two test has been done.

ID 62 – NOx severity trip in Esch

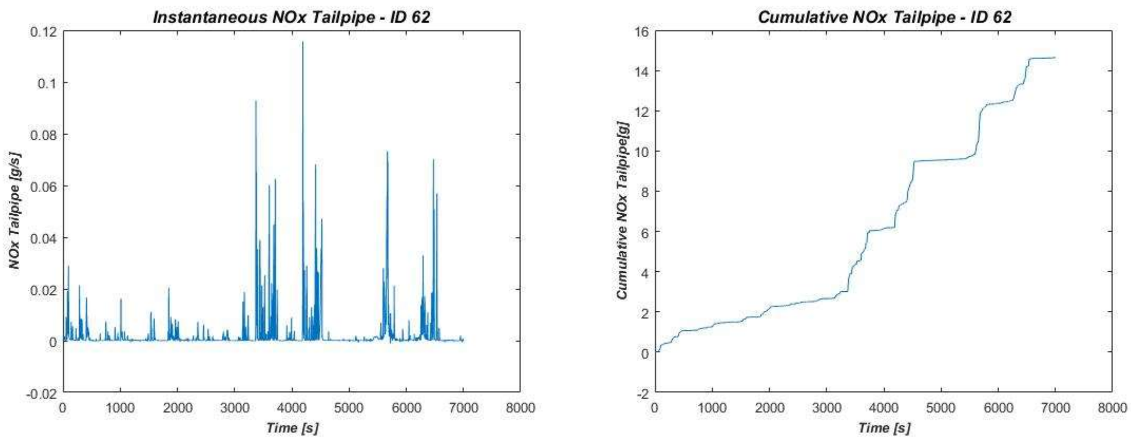


Figure 76 – NOx analysis – Severe trip – ID 62 – NOx tailpipe [g/s] & [g]

In NOx tailpipe analysis is evident as there are 4 time intervals when NOx emissions are high: the first two periods (3400/3700 and 4200/4450 seconds) are caused by road gradient as the last two periods (5600/5700 and 6450/6550) are caused by a DPF regeneration which has occurred in different phases.

Road gradient

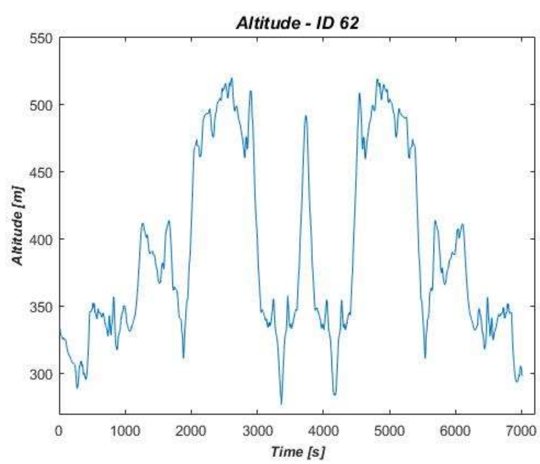


Figure 77 – NOx analysis – Severe trip – ID 62 – Altitude profile

It is clear how the first two instantaneous tailpipe NOx peaks occur during two different climbs. This happens for two different reasons:

- High production of NOx because of high load (accelerator pushed 100%) and high engine speed peaks which bring the engine to work with lower EGR level;
  This reason is reinforced by the fact that instantaneous NOx emissions engine-out are higher than the other parts of the test.

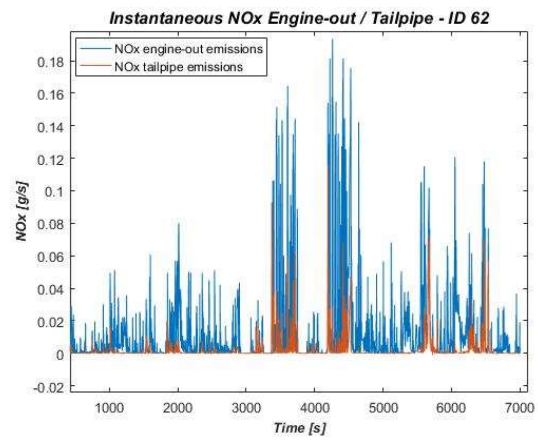


Figure 78 – NOx analysis – Severe trip – ID 62 – Instantaneous NOx engine out vs tailpipe

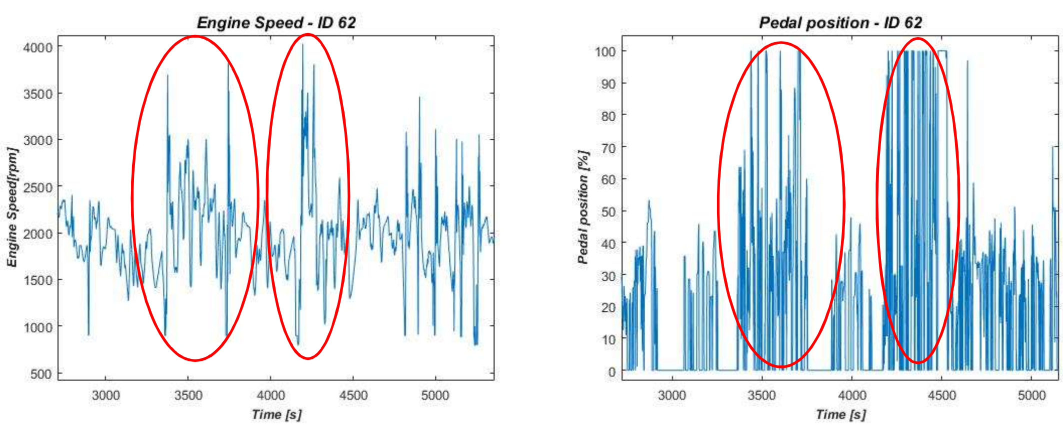


Figure 79 – NOx analysis – Severe trip – ID 62 – Engine speed & Pedal position

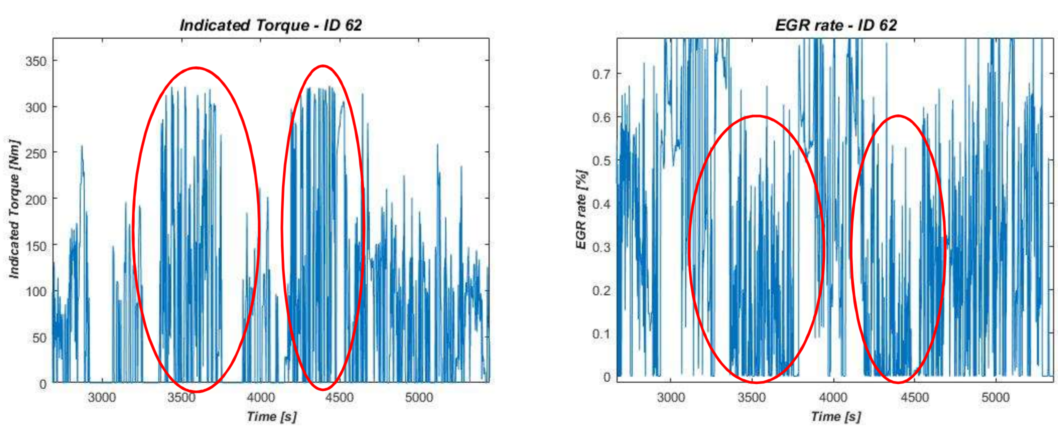


Figure 80 – NOx analysis – Severe trip – ID 62 – Indicated torque & EGR rate

- SCR 2 NOx conversion efficiency low in these time intervals because of low NH_3 stored (because of low SCR temperature) and low time spent by the exhaust in the catalyzer (because of high exhaust flow).
  The decrease of after treatment temperatures happens because during the downhill the accelerator is not pushed and, so, without combustion, the temperature of exhaust decreases and it cools the SCR.
  After the downhill, immediately the climb starts and so SCR temperature needs some seconds to get warmer and work with higher conversion efficiency.

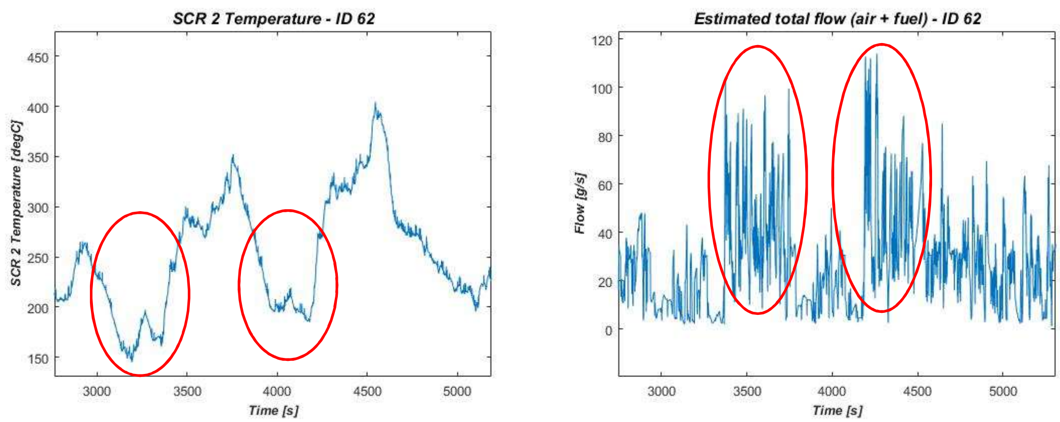


Figure 81 – NOx analysis – Severe trip – ID 62 – SCR 2 Temperature & Estimated flow

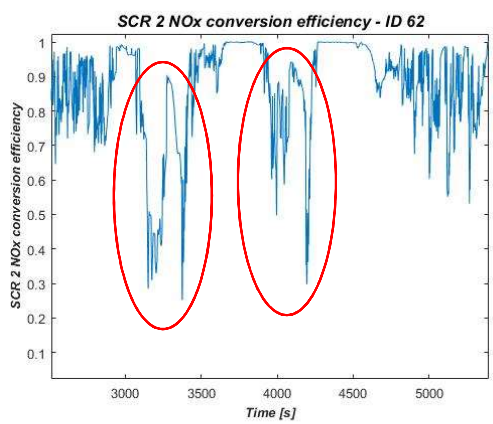


Figure 82 – NOx analysis – Severe trip – ID 62 – SCR 2 NOx conversion efficiency

This phenomena is very relevant in NOx emission production because it contributes to the 40 % of the total NOx tailpipe production during the test.

DPF Regeneration

Another very important phenomena which happened during this test and increased a lot NOx emission production is the DPF regeneration which contributes to the 35 % of the total NOx tailpipe production during the test.
DPF regeneration happen in three phases and the most important in NOx emission are the last part of the first one and the third.

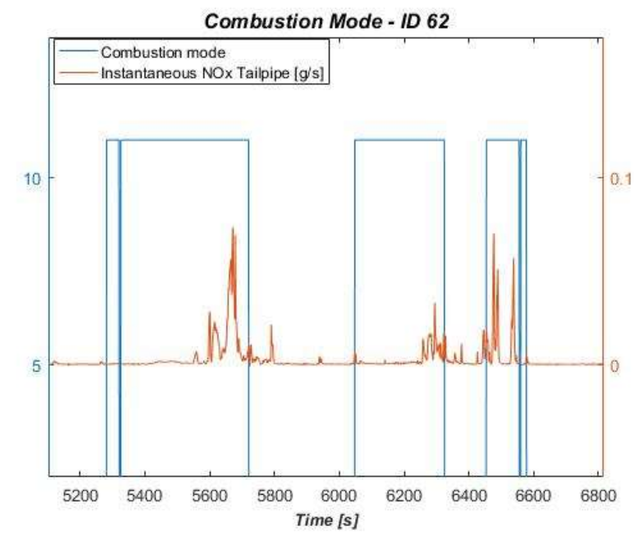


Figure 83 – NOx analysis – Severe trip – ID 62 – Combustion mode

The increase of NOx is caused by the EGR which is cut during the regeneration: HP EGR is cut to let the hydrocarbons that are produced with post – injections not to come back at the intake but to reach the DOC in order to increase the DOC and, consequently, the DPF temperature and LP EGR is cut to avoid a further increase of exhaust temperature as it has been already explained.

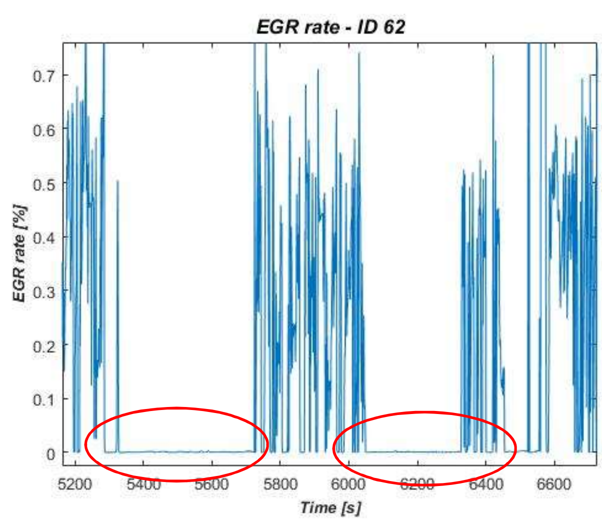


Figure 84 – NOx analysis – Severe trip – ID 62 – EGR rate

In the first part of the first phase and in the third phase of the DPF regeneration, EGR is still cut and, so, an high quantity of NOx is produced engine – out but there are no peaks tailpipe because SCR 1 and 2 temperatures are lower and, so, NH_3 stored is higher: this contributes to increase its NOx conversion efficiency.
In the other phases of DPF regeneration the SCR temperatures increase and this cause a decrease in NH3 stored and, so, in catalyzer NOx conversion efficiency.

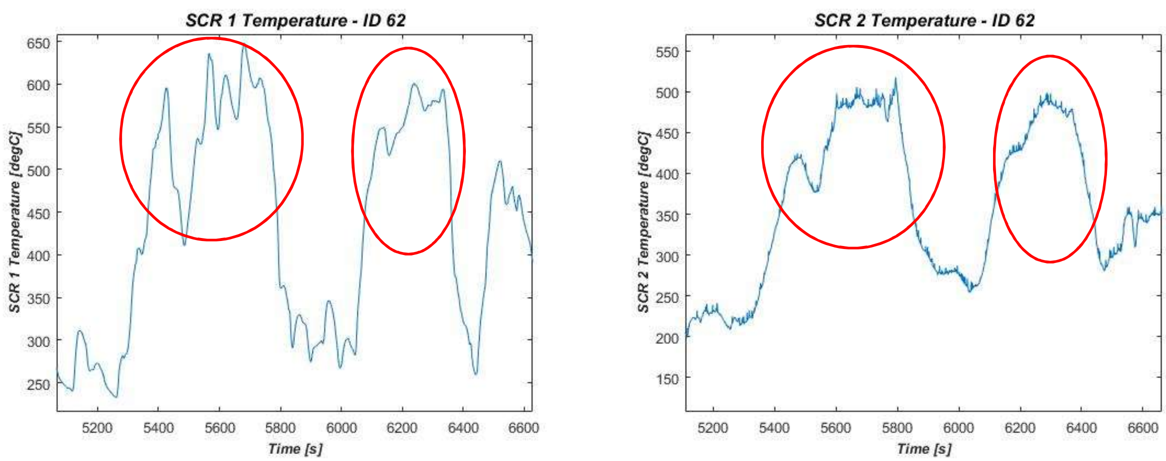


Figure 85 – NOx analysis – Severe trip – ID 62 – SCR 1 & 2 Temperature

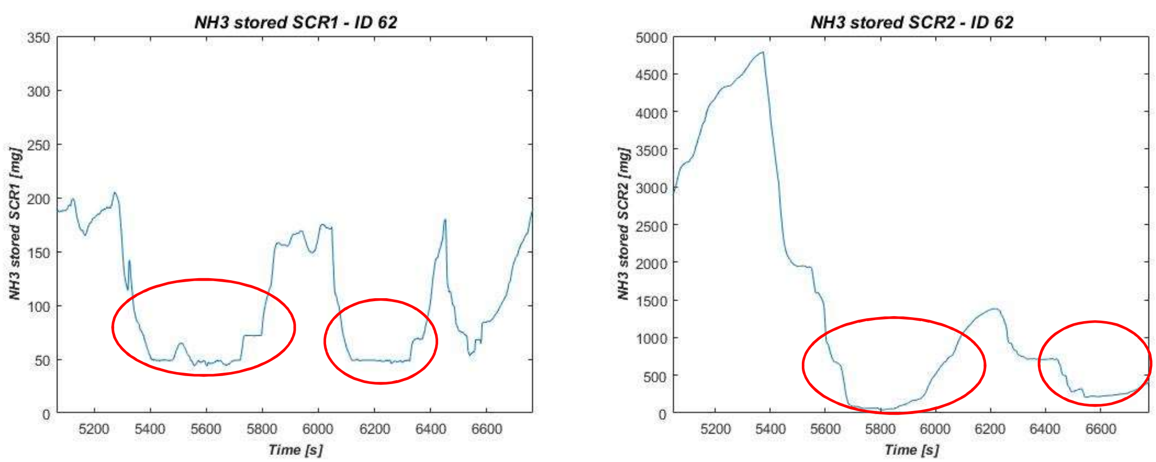


Figure 86 – NOx analysis – Severe trip – ID 62 – SCR 1 & 2 NH_3 stored

The two phenomena that have been described are very important because, even if they last for less than the 20 % of the total test time, they contribute for the 75 % of the total NOx tailpipe production.

ID 220 – NOx severity trip until Luxembourg city

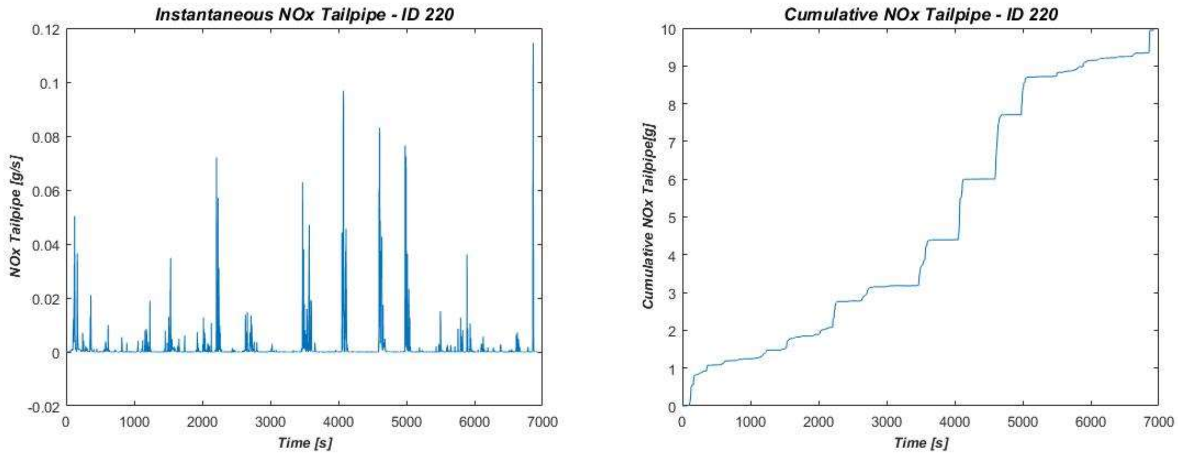


Figure 87 – NOx analysis – Severe trip – ID 220 – NOx tailpipe [g/s] & [g]

The last test studied in this analysis is a trip done from Delphi in Bascharage to the beginning of Luxembourg in a road characterized by different gradients in order to study the increase of NOx with severe conditions.
It is evident as the shape of cumulative NOx tailpipe is a step shape characterized by long time intervals with NOx emissions really low and very short time interval with high NOx emissions.
Studying NOx peaks is fundamental because, even if they last for the 5 % of the total test time, they contribute to the 70 % of total NOx emissions measured tailpipe.
All the peaks happen at the beginning of the hills immediately after the end of downhills.

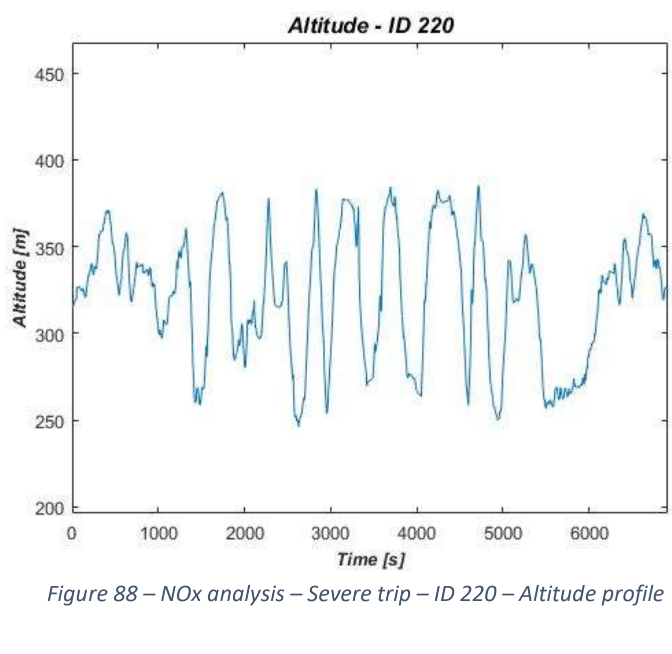


Figure 88 – NOx analysis – Severe trip – ID 220 – Altitude profile

Three different cases can be found in this test:

1. NOx engine out high peaks which happen because of strong accelerations (accelerator totally pushed, indicated torque high and, consequently, low EGR level) which become NOx tailpipe high peaks because they are only partially reduced by SCR because of low SCR efficiency caused by high space velocity (peaks at 2210, 3570, 4070, 4980 and 6860 seconds);
2. NOx engine out small peaks which become NOx tailpipe high peaks because SCR efficiency really low because of SCR temperature lower than 200 degC (peaks at 3470 and 4600 seconds);
3. NOx engine out small and high peaks which are highly reduced by SCR because of high SCR NOx conversion efficiency (peaks at 4120 and 5010/5030 seconds).

One example for this case will be presented explaining more precisely which parameters influenced mostly NOx production and reduction.

1. Peaks at 2210/2230 seconds

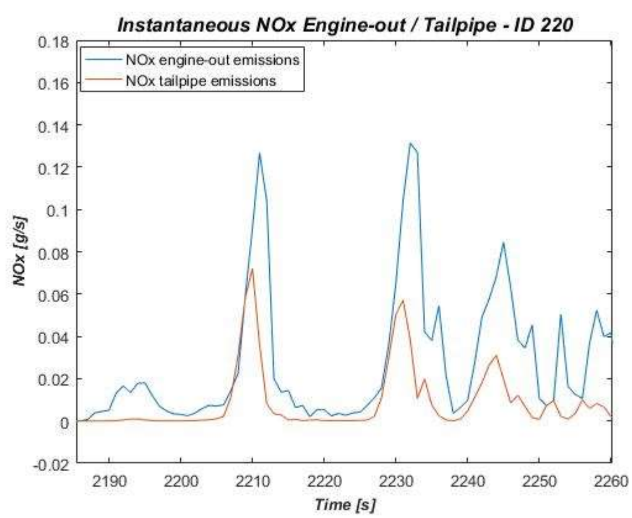


Figure 89 – NOx analysis – Severe trip – ID 220 – NOx engine out vs tailpipe [g/s]

NOx engine out peak is caused by an high torque demanded by the driver pushing the accelerator completely. This causes an high value of indicated torque which brings the engine to work at level with lower EGR rate.
SCR 2 is not able to totally reduce NOx because it is working with lower conversion efficiency because of and high exhaust flow and consequent high exhaust space velocity (low time spent by the exhaust in the catalyzer).

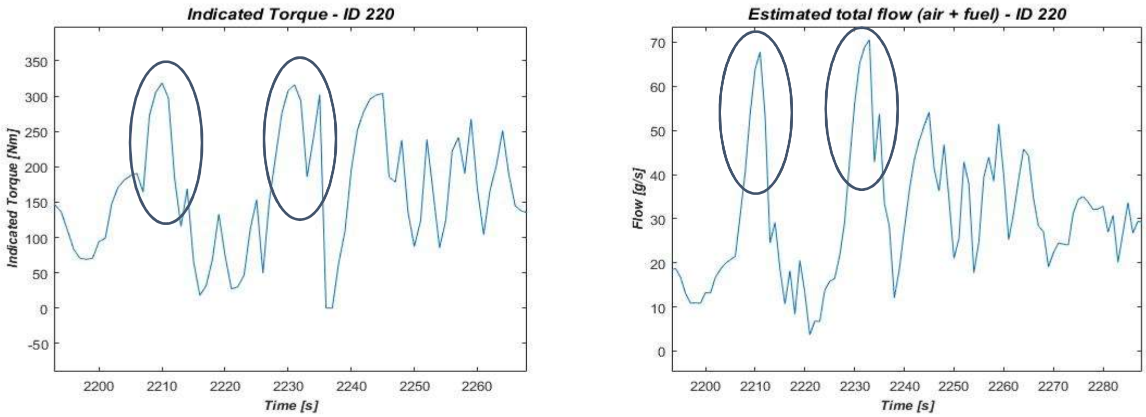


Figure 90 – NOx analysis – Severe trip – ID 220 - Indicated torque & Estimated flow

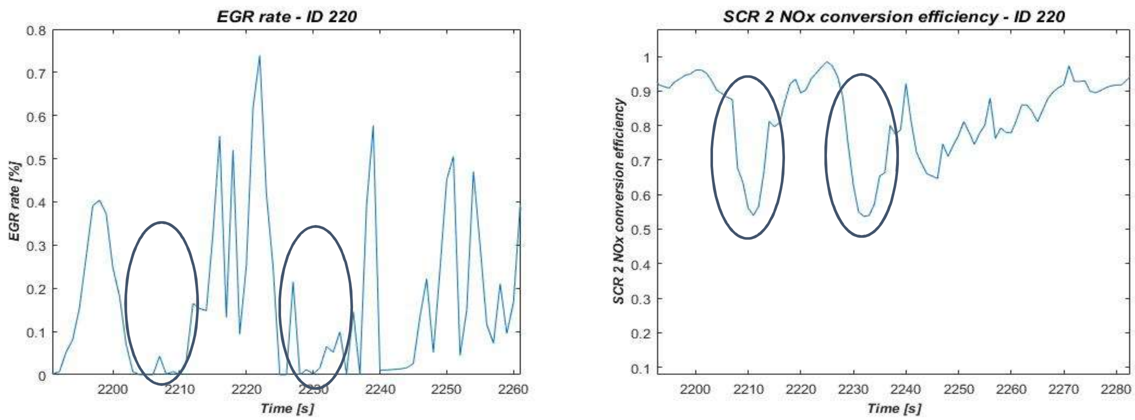


Figure 91 – NOx analysis – Severe trip – ID 220 – EGR rate & SCR 2 NOx conv. eff.

2. Peaks at 3470 seconds

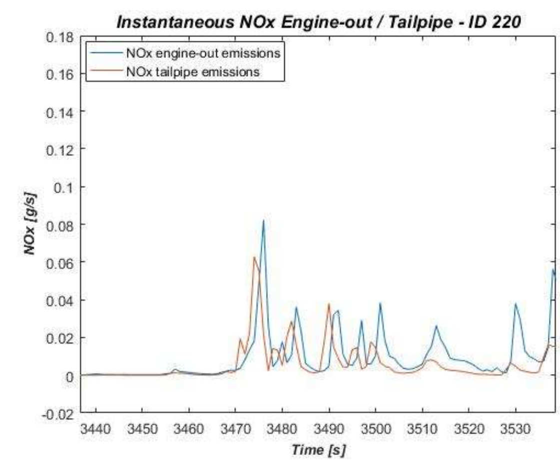


Figure 92 – NOx analysis – Severe trip – ID 220 – NOx engine out vs tailpipe [g/s]

In this case NOx tailpipe peak is comparable to the previous case even if the NOx engine out peak is much lower: this happens immediately after the end of the downhill.
The driver torque demand is not so high because it is a flat part of the trip but SCR temperature is really low because the previous part of the trip was characterized by the absence of combustion (foot off for the long part of the downhill).
For this reason SCR efficiency is low and, so, the main part of NOx produced are not reduced.

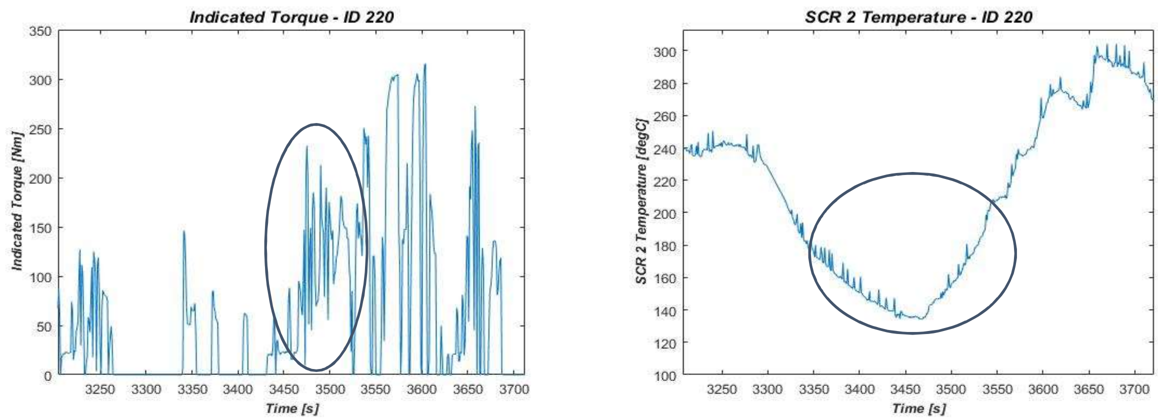


Figure 93 – NOx analysis – Severe trip – ID 220 – Indicated torque & SCR 2 T

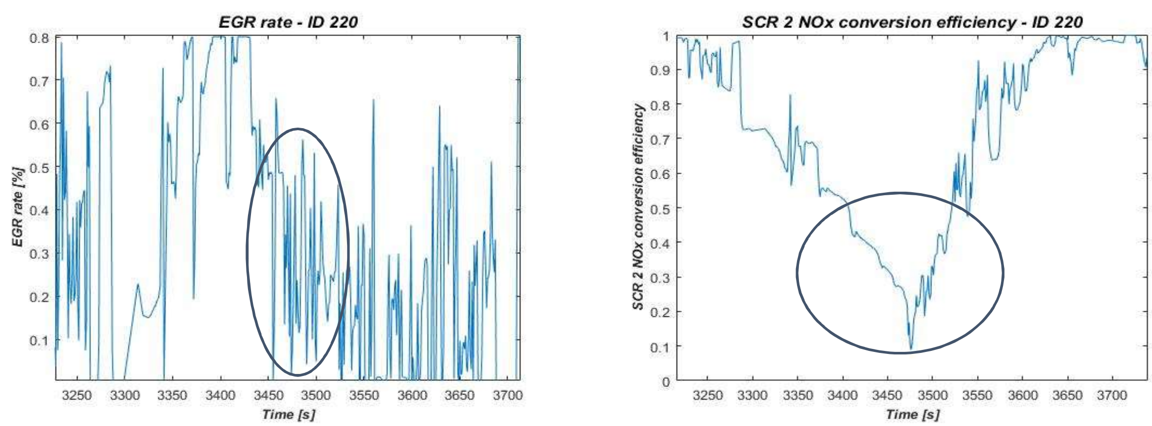


Figure 94 – NOx analysis – Severe trip – ID 220 – EGR rate & SCR 2 NOx conv. eff.

3. Peaks at 4120 seconds

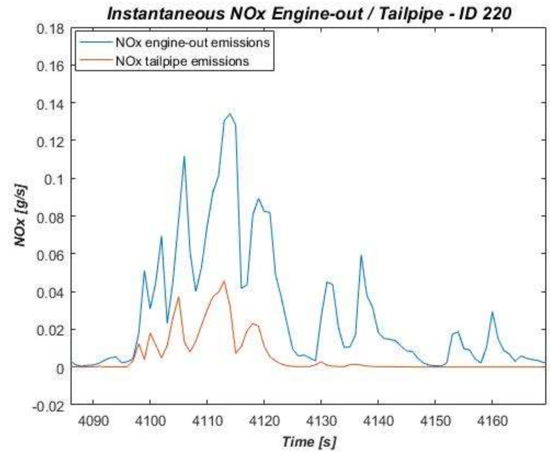


Figure 95 – NOx analysis – Severe trip – ID 220 – NOx engine out vs tailpipe [g/s]

High NOx peaks measured engine – out for the same reasons as before (low EGR rate because of high load requested by the driver) but lower NOx peak measure tailpipe because of higher SCR 2 temperature and so SCR 2 NOx conversion efficiency.

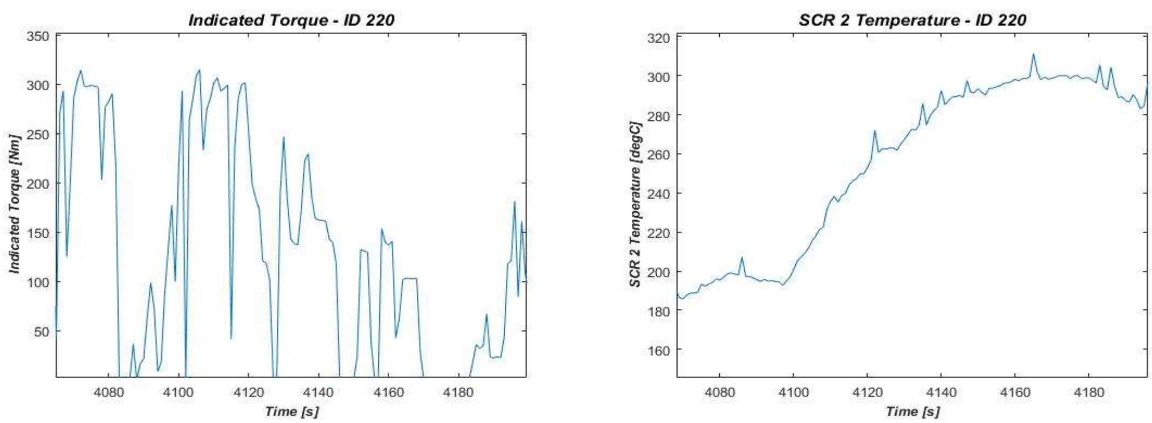


Figure 96 – NOx analysis – Severe trip – ID 220 – Indicated torque & SCR 2 temperature

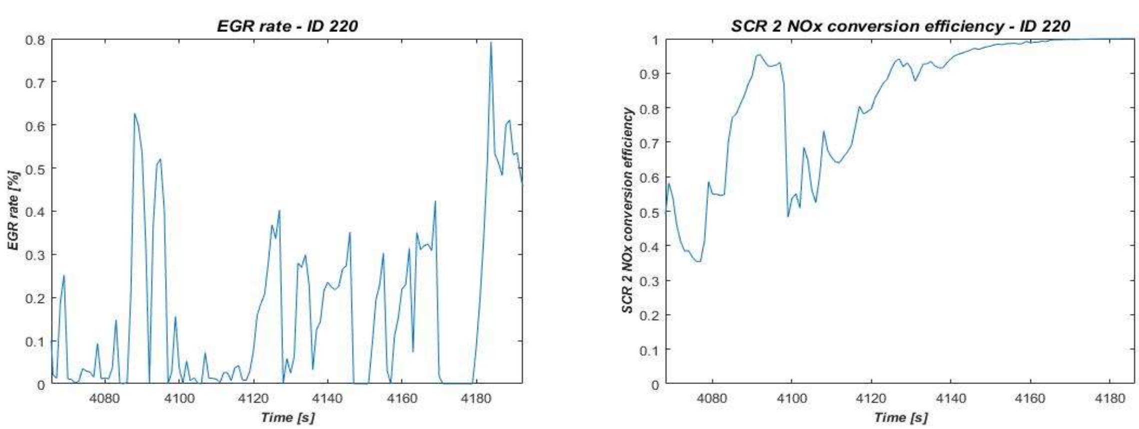


Figure 97 – NOx analysis – Severe trip – ID 220 – EGR rate & SCR 2 NOx conv. eff.

Conclusion

A deep NOx analysis has been done in the Honda T 113 tests in order to detect conditions which are more severe in NOx emissions.
The final goal of this study is to provide knowledge to create, in the future, a methodology which is able to say how much a particular RDE test is severe for emissions.
This need has arisen because in the future regulation each vehicle will have to respect emission limits for any RDE test driven and, so, for an automotive company is fundamental to know how much is the percentage to pass or to fail a random RDE test.
It is not easy to achieve this aim because NOx emissions are characterized by long time intervals when they are quite constant and some instants when high peaks are measured: analyze the reasons of the creation of the peaks is fundamental in order to understand how much is the probability to have the presence of one or more of them in a random test.

NOx emission analysis is characterized by two focus points:

1. How much NOx are produced by the engine;
2. How much NOx are measured tailpipe.

The first aspect is mainly influenced by the combustion temperature (mainly influenced by the EGR rate) and the air fuel ratio.
If EGR rate increases, an higher quantity of exhaust is recirculated in the chamber replacing air, and, so, the temperature of the combustion decreases and less NOx are produced.
It is important to notice how at high load, EGR rate is decreasing (until reach the 0 %) because by lowering chamber temperature, engine performances get worse.
Moreover at high load, in a diesel engine, the mixture get closer to the stoichiometric and, if EGR increased, the mixture would become richer (because exhaust gas would replace air in the chamber) and there would be the risk to overpass the smoke limit.
If the air fuel ratio increases, more oxygen is present in the chamber and, so, more NOx are produced.

The second aspect is influenced by SCR efficiency and urea injection strategy.
The efficiency increases if the catalyzer temperature increases (faster chemical reaction), the exhaust flow decreases (more time spent by the exhaust in the catalyzer), the NH_3 stored increases and the ratio NO_2/NO increases (because it gets closer to 50 % and a faster NOx reduction reaction can happen).
Last, NOx conversion is ruled by the ECU strategy about the quantity of injected urea: some car manufacturers prefer to reduce urea usage being more focused on the production of engine-out NOx as some other prefers to inject more urea limiting less the NOx production.

Conclusion

The main body of this work regards the development of two Matlab tools which are able to analyze entirely an RDE test, according RDE Pack 3 and RDE Pack 4, investigating its validity and its results in order to emulate the PEMS equipment previously rented from external companies.
In order to reach this final goal, first of all, a deep study about present and future RDE regulations has been done in the 1st chapter of the thesis.
Secondly, tools have been validated feeding it with the same input as PEMS Horiba PC and Emroad software and comparing their results.
Thirdly, they have been changed in order to be able to work starting from ECU data, independently from PEMS measurements.
Finally they have been converted in two executable files in order to make them usable by external users without the necessity of Matlab.
In order to let people use them in a more comfortable and quick way some modifications have been done to the interfaces shown in the 2nd chapter of the thesis:

- In order to let the user not to write all the input data for every test which has to be post processed, input information shall be put inside an excel file with a standard format and the user has only to indicate the path on his PC where to find it;
- In order to let the user to have all the final results in one file, parameters and images are printed in the same excel file used for input information in two different sheets.

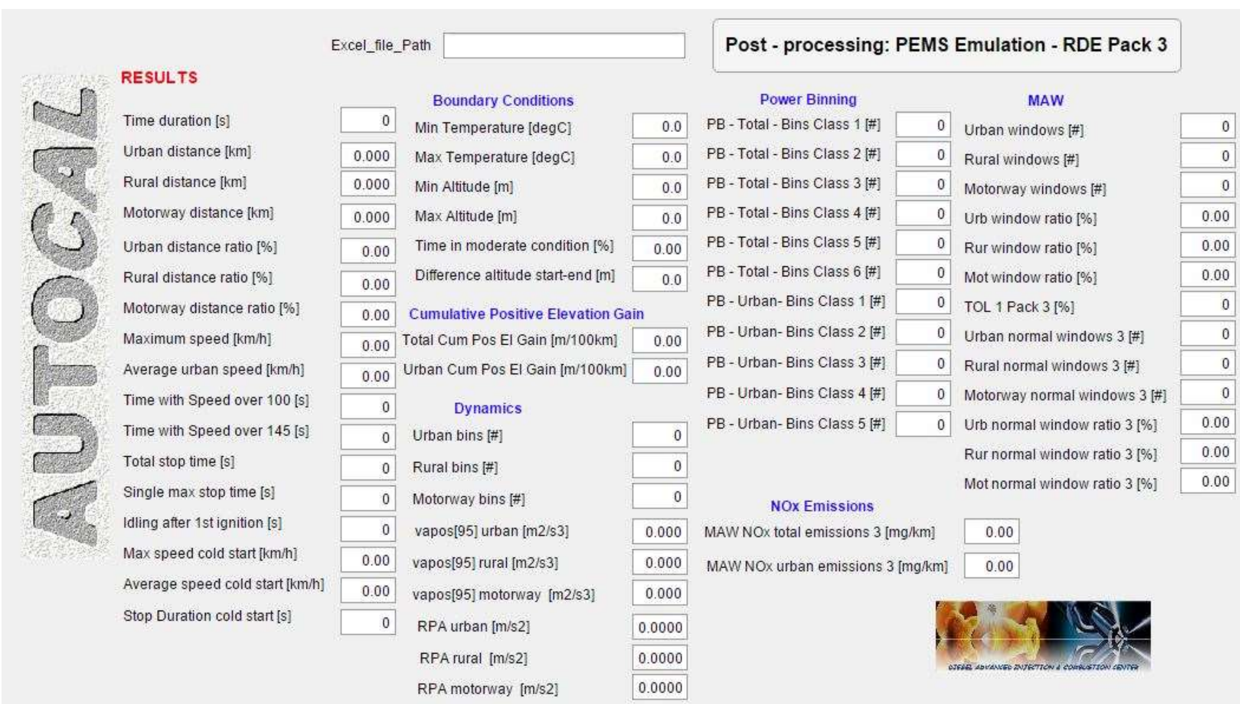


Figure 98 – Conclusion – Final Interface Matlab Emulation Tool RDE Pack 3

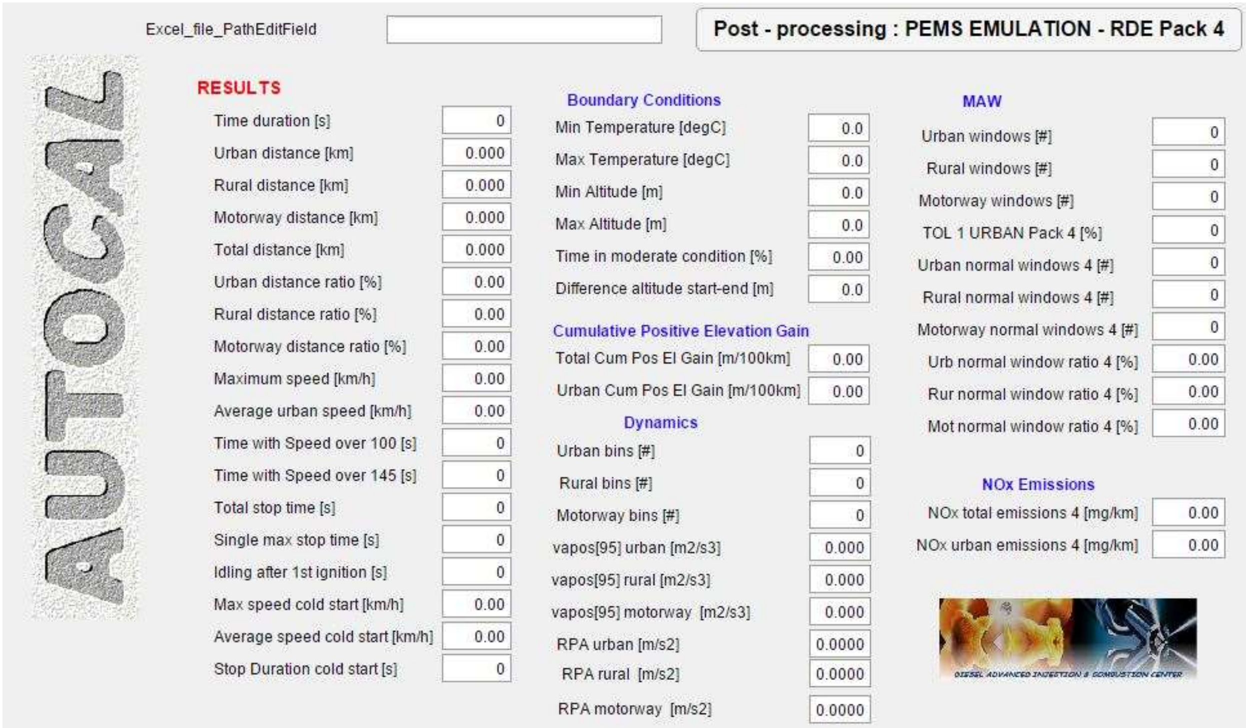


Figure 99 – Conclusion – Final Interface Matlab Emulation Tool RDE Pack 4

The last part of this work, instead, regards a NOx instantaneous analysis done for a tested vehicle in order to investigates which are the main causes of NOx production and emission. Several real driving trips have been defined and different driving styles have been investigated with the intention to enhance engine and tailpipe NOx emissions. The goal of this work was to define a set of tools to help the development team to identify the robustness of a calibration to RDE tests variability.

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