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Investigation on the assessment of real world CO₂ emissions using simulation and PEMS data

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Summary

This report summarizes the work conducted by LAT in the context of a feasibility study funded by the International Council on Clean Transportation (ICCT). This study investigated the possibility to evaluate real world CO_2 emissions with generic simulation models developed on the basis of PEMS data and RDE recordings. To this aim, a validated model for a vehicle equipped with start-stop and regenerative braking was used in order to specify and investigate the difficulties and limitations of such an approach. At a second step, a new vehicle model with generic characteristics, such as the engine map and the powertrain losses, was created and compared against the same PEMS data, providing satisfactory results. Finally, cold- and hot-start simulations for NEDC, WLTC, FTP, ERMES and Artemis were conducted providing CO_2 emissions for different driving patterns. The present work constitutes a good basis for the rationale that could underpin an assessment of real world CO_2 emissions and fuel consumption. Further investigation that will cover the existing vehicle and engine technologies, such as gasoline port and direct injection, is needed in order to support and extend the findings of this work.

Keywords

RDE, PEMS, engine map development, real world simulations

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1 Introduction

This report summarizes the work conducted by the Laboratory of Applied Thermodynamics (LAT) in the context of a feasibility study funded by the International Council on Clean Transportation (ICCT) concerning the possibility to assess real world CO_2 emissions using simulation and Real Driving Emission (RDE) measurements.

In the first section of this report, a brief background and the objectives of the study are described. The second section describes the methodology followed in this exercise, the vehicle model that was used and the simulation platform. The third section analyses the measurements, the simulation results from the original validated vehicle model as well as from the generic one and the results for various driving cycles in cold and hot start engine conditions. Finally, a conclusion section highlights the main findings.

1.1 Background

Currently, European CO_2 emission and fuel economy targets for the automotive sector are based on the New European Driving Cycle (NEDC), a driving cycle which was not originally designed for this purpose. This has caused an increasing gap between the fuel consumption experienced from average drivers (especially from 2000 onwards), and the respective type approval value reported by manufacturers.

This gap is expected to decrease after the introduction of the new Worldwide harmonized Light vehicles Test Procedure (WLTP), however, it will not disappear. This is attributed to the fact that still WLTP covers only a limited area of the engine operating range, although wider than the respective of NEDC. Consequently, manufacturers will still have the possibility to develop fuel economy measures applicable only within this area and follow different strategies in the remaining operating range of the engine. Therefore it is of particular importance to explore the possibilities to utilize real world test data and follow a simulation approach in order to assess real world CO_2 emissions, i.e. cover the wider possible (if not the whole) area of the engine operating range.

1.2 Objectives of this study

This project aims at investigating the possibility to use PEMS measurements to reconstruct accurate engine maps which will be further employed in vehicle simulation models to provide fuel consumption and CO_2 emission values for different cycles and driving profiles. This exercise is a scoping study that may underpin the development of future Regulation and intends to suggest future steps towards this direction.

The main targets of this scoping study are to:

• Develop the methodology to be applied on the assessment of real world CO₂ emissions using simulation models, developed on the basis of PEMS data

- Apply the methodology to one indicative vehicle, evaluate the results and make the necessary improvements
- Identify and highlight important issues that need further investigation

The final outcome of this scoping study can give the directions of research for the development of a procedure that could use real world (RDE) testing for Regulatory purposes.

2 Methodology

The basic steps of the approach followed are summarized below:

- 1. An existing validated vehicle model with OEM data (hereinafter called "*original model*") is compared against PEMS measurements. This step highlights any inaccuracies and deviations of the *original model*.
- 2. The PEMS measurements are used to back calculate the engine map of the tested vehicle. This is performed by stretching an existing vehicle model (hereinafter called "*generic model*") with partial "generic" characteristics (engine map, powertrain losses).
- 3. The reconstructed engine map (from step 2), is used in a new vehicle model (hereinafter called "*reconstructed model*") and the results are compared against the measurements and the results of the *original model*.
- 4. The final *reconstructed vehicle model* is used to simulate the fuel consumption and CO₂ emissions for various driving cycles (i.e. NEDC, WLTP, CADC, ERMES, FTP).

A schematic of the above procedure is given in Figure 1.

In the first step, the real world measurements are simulated with the existing "*original model*", using OEM data. This step is expected to provide some first indications of the difficulties and the limitations of real world simulations.

In the second step, a new engine map is developed from the measurements and new simulations are performed. This new engine map is the outcome from stretching the *"generic model"*, which is an existing vehicle model with generic powertrain losses and engine map that belong to the same segment with the examined vehicle. For the generic data, the LAT's internal database is currently used.

The back calculation of the engine map is made using the existing PEMS data and forms the main input for the "*reconstructed model"*. The results of this model are compared with both the measurements and the simulations from the "*original model"* (with OEM data).

In the third step, the simulation results from the new vehicle model ("*reconstructed model"*) are compared with both the RDE measurements and the results from the "*original model"*. Finally (fourth step), the new developed vehicle model is used for the simulation of different driving cycles such as NEDC, WLTP, ERMES, CADC, FTP etc.



Figure 1: Schematic of the investigation.

2.1 Vehicle used in the Scoping Study

The vehicle used in this scoping study is the BMW X1 20d Efficient Dynamics, the main specifications of which are shown in

Table 1. This vehicle is considered a mild hybridized Euro 5 passenger car, equipped with Start-Stop and Brake Energy Recuperation. More detailed characteristics can be found in open sources¹. For the RDE measurements, AVL PEMS equipment was used. Figure 2 shows a picture of the vehicle with the PEMS installed.

The "original model" for this car was developed and validated in the framework of a previous exercise run at LAT. The Annex of this report presents details on the validation of the respective simulation model.

All the results presented herein refer to this vehicle. In the context of this feasibility study the model was not extended to other vehicles. However, the methodology can be applied to any vehicle, taking care to correctly implement its individual characteristics, either design details (e.g. engine type) or calibration features (e.g. automatic gearbox strategy).

¹ <u>http://www.cars-data.com/en/bmw-x1-sdrive20d-efficientdynamics-edition-specs/8319</u>



Figure 2: BMW X1 with installed PEMS equipment.

Fuel	Diesel
Displacement [cc]	1995
Curb weight [kg]	1465
Max Engine Power [kW @ rpm]	120 @ 4000
Max Engine Torque [Nm @ rpm]	380 @ 1750
Gearbox	6 gear manual transmission
Tires	225/50 R17
Emission standard	Euro 5
Type approval CO ₂ emissions [g/km]	119

 Table 1: BMW X1 20d Efficient Dynamics specifications

2.2 Coast down test

For the real world simulations, LAT performed a coast down test in a public site near Thessaloniki (Figure 3). The calculated coast down coefficients of the driving resistance force in Equation 1, are given in Table 2.

$$F = F_0 + F_1 \cdot v + F_2 \cdot v^2$$
 (1)

Table	2:	Driving	resistance	coefficients
-------	----	---------	------------	--------------

Coefficient	Value	Unit
Fo	203.07	Ν
F ₁	0.094172	N/(km/h)
F ₂	0.036633	N/(km/h) ²



Figure 3: Site of coast down test (coordinates: 40°40'56.6"N and 22°46'39.0"E).

The vehicle mass during the coast down test was 1710 kg and the ambient temperature was 19°C. The coast down curve used in the simulations (own tests) is given in Figure 4. Additionally, total deceleration time for the specific vehicle under NEDC, WLTP-L and WLTP-H driving resistances are provided for comparison purposes. The corresponding road loads were provided to LAT from the manufacturer.

Figure 4 shows that the total deceleration time with WLTP-H road load is very close to the measured (real world) one and significantly shorter (i.e. higher road load) than NEDC's. This behavior should not be generalized for the whole vehicle fleet since WLTP road load is vehicle specific.



Figure 4: Total deceleration time with different driving resistances for the test vehicle BMW X1.

2.3 Simulation platform

The simulation platform used by LAT for this study was AVL CRUISE. This is a micro simulation tool used for emissions and powertrain analysis. It covers a wide range of vehicle types and is characterized by fast calculation time with a multi-physics solver, as well as modular and component oriented modelling approach and onboard integration platform.

Figure 5 depicts the graphical user interface of CRUISE, together with the main vehicle components that were used for the simulations: the engine, the transmission system (which consists of the clutch, the final drive and the gearbox), the brakes, the wheels and the electrical system (which consists of the generator and its pulley, the battery, the starter and the electrical consumer along with their controllers).



Figure 5: CRUISE Graphical user interface.

3 Results

3.1 Measurement results

Partial RDE measurements (not fully compliant with the RDE regulation) were available at LAT from a previous internal project. The available instantaneous data from those tests include time, altitude and vehicle speed provided by the installed GPS, ambient temperature, engine load, battery voltage, engine coolant temperature, engine speed, intake air temperature, air flow rate, vehicle speed from the vehicle's OBD and CO₂, CO, NO₂ and NO_x emissions from the PEMS instrument, while fuel consumption was calculated. For the validation simulations, time, altitude, vehicle speed from the GPS, engine speed from the OBD and CO₂ emissions from the PEMS instrument, together with the calculated fuel consumption, were used.

A brief summary of the available trips performed in the past can be found in Table 3. For the validation simulations, knowingly erroneous measurements due to high internal temperature or absence of data (e.g. trip 16, trip 21) were excluded from the investigation. From the remaining tests, trips 18 and 20 were chosen for the investigations according to their different characteristics (trip length, duration, max speed etc.). Still a slight error is expected, since the tests were conducted with open windows, while during the coast-down test the windows were closed.

Trip code	Date	Trip length [km]	Trip duration [s]	Max speed [km/h]	Average speed (with idle) [km/h]	Idling time [s]	Comment 1	Comment 2
Trip 15	June 24, 2015	44.0	3406	128.4	46.5	402	Front windows open	-
Trip 16	June 24, 2015	11.8	2045	81.6	20.8	541	Front windows open	Problematic measurements, PEMS internal temperature > 45°C
Trip 17	June 25, 2015	31.8	3600	88.4	31.8	487	Front and rear window open	-
Trip 18	June 25, 2015	51.7	3145	143.4	51.6	496	Front and rear window open	Chosen measurement for the investigation
Trip 19	June 25, 2015	8.3	2574	64.3	11.6	824	Front and rear window open	-
Trip 20	June 25, 2015	15.9	2287	99.3	25.0	574	Front and rear window open	Chosen measurement for the investigation
Trip 21	June 26, 2015	8.2	3600	60.0	8.2	2180	Air Condition full open	No GPS connected (no vehicle speed, no altitude). Calculations with OBD vehicle speed
Trip 22	June 26, 2015	7.9	1828	61.0	15.6	685	Air Condition full open	No GPS connected (no vehicle speed, no altitude). Calculations with OBD vehicle speed

Table 3: Summary of the RDE measurements with BMW X1.

3.2 Validation model results

After setting up the model in CRUISE using the characteristics of each trip (vehicle speed, altitude, gear shifting), simulations for the various road loads, i.e. NEDC, WLTP-L, WLTP-H and own tests, were conducted. The results for trips 18 and 20 are summarised in Table 4 and Table 5 respectively.

Trip 18	Measurement (23.6°C)	leasurement NEDC driving WLTP-L driving (23.6°C) resistance resistance		WLTP-H driving resistance	Own tests driving resistance (19°C)
Results [g/km]	153.1	142.8	146.2	154.0	154.2
Divergence from measurement [g/km]	-	-10.3	-6.9	0.9	1.1
Divergence from measurement [%]	-	-6.7%	-4.5%	0.6%	0.7%

Table 4: Simulation results and divergence from measurement for trip 18.

Trip 20	Measurement (23.6°C)	NEDC driving resistance	WLTP-L driving resistance	WLTP-H driving resistance	Own tests driving resistance (19°C)
Results [g/km]	255.5	222.4	229.9	234.6	235.4
Divergence from measurement [g/km]	-	-33.1	-25.6	-20.9	-20.1
Divergence from measurement [%]	-	-13.0%	-10.0%	-8.2%	-7.9%

Table 5: Simulation results and divergence from measurement for trip 20.

Simulations with NEDC driving resistance give the highest (negative) divergence from the measurement for both trips, as expected. Similar are the results when using WLTP-L driving resistance. When WLTP-H road load was used, the divergence was reduced (trip 20) and in the case of trip 18 changed signed. When using own tests driving resistance, the difference from the measurement is similar to the case of WLTP-H road load for both trips.

Figure 6 illustrates the measured (blue line) and simulated (red line) cumulative fuel consumption (FC) of trip 20. The green line corresponds to the second-by-second difference between the measured and the simulated FC. The orange line is the 5% margin of the difference. During the first seconds of trip 20, an underestimation in FC is observed which remains constant until approximately 500 s. As it will be further discussed below, this is attributed to the alternator consumption (alternator current not measured in these tests).



Figure 6: Trip 20; measured and simulated cumulative FC.

In Figure 7 the measured and simulated instantaneous FC along with the driving profile are depicted.



Figure 7: Trip 20; importance of alternator consumption.

In the first \sim 70 seconds of the trip, while the engine is idling, the measured FC is above the simulated one, resulting in the initial underestimation of the simulated FC until

approximately 500 s. The most probable reason for this is an extra FC caused by the alternator, which, at the current state, the vehicle model cannot simulate since it uses a generic electrical system. Then, the deviation increases between 500 - 1500 s. This is partially attributed to the driver behavior which generates peaks in the FC which are not sufficiently simulated with the generic driver (Figure 8). In addition, the difference increases with the idling events that occur around 1000 and 1350 s. With a proper driver calibration and by measuring the alternator consumption during the trip, it is expected that the difference between the measured and the simulated signals can be minimized.



Figure 8: Trip 20; measured and simulated FC between 500 – 1500 s.

Similarly to Figure 6, Figure 9 illustrates the measured and simulated cumulative FC of trip 18, as well as the difference between them without the altitude effect. From 400 to 1000 s, an underestimation is observed followed by an overestimation until 1500 s.

Looking into the instantaneous signals of the measured and simulated FC from 500 to 1200 s (Figure 10), it can be easily distinguished that the measured signal is above the simulated for the given time period and the difference constantly increases. However, areas where the measured signal is below the simulated one for the given time period are also present. This may be attributed to changes in the engine load caused by uphill and/or downhill driving. This assumption is enhanced by observing the signals from 1200 to 1600 s, where the deviation between measurement and simulation not only decreases, but simulated FC even exceeds the measured one.



Figure 9: Trip 18; measured and simulated cumulative FC without altitude effect.



Figure 10: Trip 18; measured and simulated FC between 500 – 1500 s without altitude effect.

After introducing the instantaneous altitude in the simulation for trip 18, the simulated FC is improving (Figure 11, Figure 12). A slight constant overestimation in the simulated FC until 2500 s, may be attributed to road load inaccuracies. Still the divergence is below 5%.

After 2500 s, idling events occur (Figure 13) and the measured FC increases when compared to the simulated one. This effect, similarly to trip 20, cannot be simulated unless the alternator current is measured during the test.

To sum up, the FC predicted with a validated vehicle model when compared to the FC measured under real world conditions, can be accurately simulated if recordings of the altitude and the alternator consumption are available. Table 6 summarizes the data already being recorded in a PEMS test and data that are not recorded in a PEMS test, but are essential for real world FC simulation.



Figure 11: Trip 18; measured and simulated FC between 500 – 1000 s with altitude effect.



Figure 12: Trip 18; measured and simulated cumulative FC with altitude effect.



Figure 13: Trip 18; measured and simulated FC between 2500 – 3200 s with altitude effect.

Table 6: Data included in PEMS and data not included in PEMS but are essential for this exercise.

Data already included in PEMS	Data not included in PEMS but are essential for this exercise			
Time (GPS)	Coast down test			
Vehicle speed (GPS)	Alternator current measurement			
Altitude (GPS)	—			
Engine speed (OBD)	—			
CO ₂ emissions	—			
Fuel consumption	_			

3.3 Generic model results

In the context of another exercise, LAT has developed a number of validated vehicle models (mostly Euro 5) using detailed necessary input data which were largely provided to LAT by the respective OEMs, such as fuel consumption maps, powertrain losses, inertia moments and gear shifting strategy. The data for the development of the vehicle models constitute the LAT database. Some of these data were also provided to LAT by JRC.

Using the above data, LAT developed a template vehicle model topology² that underpins the development of an "average" generic model. The main components of the vehicle model can be seen in Figure 5 and consist of the engine, the transmission system, the wheels and the electrical system. The same topology can be used for different micro-hybridized vehicles, for different engine sizes, fuels etc., but not for vehicles with advanced configurations i.e. hybrids, PHEVs, range extenders. Then, this template model was fed with the data essential for the simulations from the LAT database (engine map, full load curve, motoring curve, powertrain losses).

The results from the simulation of trip 18 can be seen in Figure 14. Minor differences are observed when comparing them to the results generated from the validated vehicle model. This may be due to the fact that one of the engine maps used to create the generic one for this vehicle segment, belonged initially to the vehicle used in this study. However, this generic map was the average from three different vehicles.



Figure 14: Trip 18; measured and simulated FC between 500 – 1000 s with the generic vehicle model. In the table, the overall results are shown.

The simulation results with the generic model indicate that no stretching was necessary to the used generic engine map. Possibly in another case study, a correction of the generic engine map may be needed to fit the end results, due to inconsistencies between the generic and the real FC map.

² Tsokolis D, Tsiakmakis S, Triantafyllopoulos G, Kontses A, Toumasatos Z, Fontaras G, et al. Development of a Template Model and Simulation Approach for Quantifying the Effect of WLTP Introduction on Light-Duty Vehicle CO_2 Emissions and Fuel Consumption SAE Paper No. 2015-24-2391, 2015.

3.4 Driving cycle results

After the development of a vehicle model with generic data that can successfully reproduce real world measurements with an acceptable error margin, cold and hot driving cycle simulations are performed. The cold start model used in the specific project was calibrated in the context of a different exercise for different road load, thus, the absolute values should be carefully assessed, in particular since the Artemis and ERMES cycles are usually used in testing exercises as hot start cycles.

The results from the driving cycle simulations are given in Table 7. The range of the cold start cycles is between 156.6 g/km (ERMES) and 245.8 g/km (Artemis Urban). In addition, LAT measurements with the same "own tests" road load for some of those driving cycles are also provided for comparison purposes. In the real world tests and simulations the start-stop system was not operating; the driving cycle simulations assume an operating start-stop.

Since the initial SOC for the measurements is unknown, for the simulations it was set at the electrical system's "sustain-mode" operation level.

CO ₂ simulated [g/km]	NEDC	WLTC	FTP- 75	Artemis Urban	Artemis Road	Artemis Motorway 130 km/h	Artemis Motorway 150 km/h	ERMES
Cold start (19°C RL)	156.9	155.0	170.5	245.8	153.8	177.2	183.9	157.4
Cold start (23.6°C RL)	156.8	154.2	170.1	245.6	153.3	176.0	182.6	156.6
Hot start (19°C RL)	151.1	152.0	165.9	234.0	150.3	176.0	182.8	155.0
CO₂ measurements [g/km]	NEDC	WLTC	FTP- 75	Artemis Urban	Artemis Road	Artemis Motorway 130 km/h	Artemis Motorway 150 km/h	ERMES
Cold start	150.8	152.3	-	-	-	-	-	-
Hot start	140.6	150.2	-	230.1	135.0	-	-	-

Table 7: Driving cycle simulations with the generic vehicle model.

3.5 Additional considerations

Further to the above analysis, below is a list of some additional points to be taken into consideration when assessing real world CO_2 emissions and fuel consumption using simulation:

- <u>Wheel/tire inertia moment</u>: In theory wheel/tire inertia moment is proportional to the rolling radius and both the dynamic rolling radius and the wheel inertia can be calculated using the characteristics of the wheels and tires. However, this is not straight forward as it is revealed from our data in Figure 16Figure 15 materials and configurations are constantly changing, hence the scatter. To reduce the uncertainty, for the validation it is preferable to use the inertia moment provided by the manufacturer.
- <u>Ambient temperature effect</u>: Ambient temperature may play a role on vehicle resistance, having a stronger impact on aerodynamic resistance (which is proportional to the square of velocity). As the effect of ambient temperature is on

air density, coefficient F_2 has to be adjusted proportionally to density change during coast-down and RDE testing. This has been done in our calculations and tests – since the temperature difference between coast down tests and actual measurements was small (<5°C) the effect on CO₂ emissions was negligible – as expected.



Figure 15: Correlation between dynamic rolling radius and inertia moment.

 <u>Engine coolant temperature effect</u>: The current RDE regulation foresees hot-start tests only, therefore engine coolant temperature is not crucial and all tests we run were hot-start. As shown above, cold-start simulation can also be provided, using a cold-start model developed in the context of another activity.

4 Conclusions – Future steps

Using a generic model and data from public sources and LAT database it was shown that the real world (RDE compliant) hot-start CO_2 emissions of a 6-speed manual transmission medium sized diesel vehicle equipped with start-stop and brake energy recuperation were successfully simulated. The error in total simulated CO_2 emission was lower than $\pm 2.5\%$ and the cumulative fuel consumption calculated over the entire test remained within $\pm 5\%$, compared to the measurements.

To achieve this accuracy the PEMS measurements of the current RDE Regulation need to be complemented with a coast-down and weight measurement of the test vehicle and on board alternator current measurement.

The CO_2 emissions over several driving cycles using the generic model were also simulated. The results indicate that the general overall tendencies and relationships between different cycles are adequately reproduced, however

- (a) particular emphasis has to be given to the road load and weight actually used,
- (b) additional information is necessary for the simulation of cold start extra fuel consumption and
- (c) further investigations may be necessary for cycles of extreme transient conditions (i.e. accelerations and decelerations).

The above provide a good basis for the rationale that could underpin a real world based assessment of fuel consumption and CO_2 emissions and the development of an adequate methodology. However, an extensive investigation is required to cover all existing different engine types, powertrains and vehicle segments, i.e. engine types (gasoline, both MPI and GDI, diesel engine types), powertrains - manual and automatic transmissions (hydraulic, double clutch) and vehicle sizes, configurations and topologies (incl. hybrid systems).

ANNEX

Validation of the "Original Model" for the BMW X1

This vehicle model has been validated against four different criteria, as described in the context of the WLTP-NEDC correlation exercise, for NEDC and WLTP, both cold and hot-start. The criteria with the respective figures for this vehicle model can be found below.

1. Accuracy of the comparison

Simulated CO₂ emissions " $\Delta Cycle$ " over a calibration cycle (*Cycle_{cal}*) and a validation cycle (*Cycle_{val}*) should be within ±2g/km against the measured emissions over those cycles. The results for the BMW X1 can be found in Table **8**.

$$\Delta Cycle = [(\underbrace{Cycle_{cal} - Cycle_{val}}_{Simulation}) - (\underbrace{Cycle_{cal} - Cycle_{val}}_{Measurement})]$$

1. Accuracy of the comparison							
	n / I <i>cu</i> o 1	Validation					
	y/km]	Cold NEDC Cold WLTP Hot NEDC Hot WLTP					
u	Cold NEDC		0.8	-0.3	0.1		
atic	Cold WLTP	-0.8		-1.1	-0.7		
Ilbr	Hot NEDC	0.3	1.1		0.4		
Ü	Hot WLTP	-0.1	0.7	-0.4			

Table 8: Criterion No 1 for the scoping study vehicle.

2. Accuracy of the end results

For a single vehicle the error in the total simulated fuel consumption (same as total simulated CO_2 emissions) should not exceed ±2.5%. The final results are summarized in Table 9.

3. <u>Consistency throughout the test</u>

Over at least 90% of the cycle duration the cumulative fuel consumption calculated on the validation cycle shall remain within $\pm 5\%$, compared to the measurements. An example of this criterion for a cold NEDC is provided in Figure 16, where the blue and the red lines correspond to the measured and simulated instantaneous cumulative fuel consumption (in g), the green is their absolute difference (in g) and the orange is the $\pm 5\%$ limit translated in absolute values (in g). The final results are summarized in Table 9.

	2. Accuracy of the end results for fuel consumption	3. Consistency throughout the test for fuel consumption		
Cycle	ΔCycle [%]	Percentage within ±5%		
Cold NEDC	0.0	95.4		
Cold WLTP	-0.6	91.7		
Hot NEDC	0.2	98.4		
Hot WLTP	-0.1	98.3		

Table 9: Summarized results for Criteria 2 and 3 for the scoping study vehicle.



Figure 16: Example of Criterion No 3.

4. <u>Correlation of measured and simulated signals for instantaneous values of at least</u> <u>three vehicle specific parameters</u>

The correlation coefficient of the measured vs. simulated signals for all 3 quantities must exceed 0.9 (or 90%) (e.g. engine speed, fuel consumption, coolant temperature, using blocks of 5 consecutive values). An example of this criterion, applied for the engine speed, is given in Figure 17. In addition, Table 10 summarizes the results for the three parameters selected (fuel consumption, engine speed and coolant temperature) as well as for vehicle velocity.



Figure 17: Example of Criterion No 4, application for the engine speed.

4. Correlation (R ²) of measured and simulated parameters					
Cycle	Fuel consumption [g/s]	Engine speed [rpm]	Velocity [km/h]	Coolant temperature [°C]	
Cold NEDC	0.94	0.99	1.00	1.00	
Cold WLTP	0.96	0.98	1.00	1.00	
Hot NEDC	0.96	0.99	1.00	1.00	
Hot WLTP	0.96	0.98	1.00	1.00	

Table 10: Summarized results for Criterion No 4 for the scoping study vehicle.

The above validation was performed in both cold- and hot-start tests. The engine map development from PEMS measurements will be performed only in hot-start engine conditions.