

Analysis of the Influence of Outdoor Temperature in Vehicle Cold-Start Operation Following EU Real Driving Emission Test Procedure

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ABSTRACT

Due to the need to properly quantify vehicle emissions in real world operation, Real Driving Emissions (RDE) test procedures will be used for measuring gaseous emissions on new EURO 6 vehicles. At the RDE 1 & 2: Commission Regulation (EU) 2016/427 of 10 March 2016 amending Regulation (EC) No 692/2008 as regards emissions from light passenger and commercial vehicles. Updated regulations have been enhanced to define RDE tests boundaries and data analysis procedures, in order to provide an accurate way to obtain representative results. The boundary conditions defined for vehicle testing include external atmospheric temperature, which can range from 0°C to around 30°C, for moderate conditions and -7°C up to 35°C for extended conditions in RDE tests. As a result of this range of possible test ambient temperature, pollutant emissions and energy consumption can vary considerably. Since the cold start phenomenon occurs in internal combustion engine (ICE) powered vehicles before the ICE reaches its most effective operation temperature, it affects both fuel consumption (due to higher heat losses) and pollutant emissions (mainly due to low exhaust temperature below activating temperature for after-treatment devices like SCR). This is an issue relevant in regular daily operations of a vehicle, which will also pose uncertainties in RDE tests. Consequently, this work studies the effect of external environmental temperature in RDE tests, focusing on the analysis of the cold-start period in energy consumption and NO_x emissions. Two vehicles (one diesel and one gasoline) were monitored, covering external temperatures from circa 1°C to 17°C (considered ranges of 5°C up to 15°C) in Lisbon, Portugal. A Portable Emissions Measurement System (PEMS) was used to collect 1 Hz data on vehicle dynamics, road topography, engine data and exhaust gas composition. Data collected on both powertrain configurations is compared and analyzed using European Commission proposed method for RDE tests, as well as other methods to observe the impact of the cold-start phenomena in the normal day-to-day usage of vehicles. For the determination of cold-start periods, coolant temperature data was used as proxy to determine cold and normal operation. Results indicate that the initial ambient temperature have impacts in the duration of the cold-start period during a RDE test but not as relevant as expected, mostly at low temperatures compared to higher temperatures. NO_x emissions can be around 30% higher in near 5°C temperatures for the diesel vehicle tested when compared with the other temperatures range. For the gasoline vehicle tested, the effect of the ambient outdoor temperature is not as significant as in diesel vehicles.

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INTRODUCTION

In order to control air quality issues at urban scale, legislation and certifications for the road transport sector have been implemented worldwide. Since light-duty and heavy-duty vehicles were responsible for about 23% of carbon dioxide (CO₂) emissions in Europe in 2014 [1], it is important to promote alternatives, namely

cleaner technologies for road vehicles with special focus on light duty vehicle, which represent 88% of vehicles in Europe in 2015 [2], to reduce the sector impacts, namely on human health.

The European Union (EU) has an important role in the worldwide vehicle manufacturing scene, since major manufacturer companies are located in its territory. Consequently, the industry follows regulations by the European Commission (EC) for the automotive

industry are constantly improving. The EC has set stringent emission limits along time and establishes the certification tests that all new vehicles must comply with [2]. The European emission standards for local pollutant emissions, also called EURO standards, are currently in phase 6 (EURO 6), and defines the acceptable limits for exhaust emissions of pollutants for new vehicles sold in EU states, namely CO, HC, NO_x and particulate matter [3]. The emission standards are defined in a series of EU directives staging the progressive introduction of increasingly stringent standards [4, 5, 6]. The reduction trend of the vehicle emissions and fuel consumption (or CO₂) until 2020 is assessed by the EEA, which releases preliminaries datasets on the CO₂ emissions performance for new vehicles each year. This is the core of the monitoring CO₂ emissions and is used by the EC to evaluate if the vehicle manufactures comply with the regulated CO₂ agreed targets [6]. Additionally to this, further pressure for cleaner vehicles is growing as a consequence of the recent defeating devices scandal where VW knowingly used defeat devices to pass cycle-based testing [7]. The fact that an OEM which, at the time of the scandal, was the number one in sales worldwide declared themselves guilty of cheating on emission testing, has changed the automotive industry in a radical way. While automotive industry in Europe has been the motor behind industrial and social progress, now faces a complex and hostile environment where Member States like Germany or Netherlands are pushing for core changes which will impact directly on how the industry operates and will hopefully motivate an accelerated technology implementation in the European market. Further to this, the current development of a regulation which will also include a CO₂ target is looking to control the increase of CO₂ due to the implementation of emission reduction technologies which may trade off pollutants with CO₂.

To verify the emission targets, specific vehicle certification procedures are used, which include performing driving cycles (predefined speed profiles) [8] on chassis dynamometer under controlled laboratory conditions, as specified in EU regulations [9]. Two driving cycles are used by the EU regulations: The New European Driving Cycle (NEDC) [10], implemented until the EURO 6c, and the World Light-Duty Test Procedure (WLTP), to be implemented in the EURO 6d in 2017 [10, 11].

Both driving cycles have suffered criticism regarding their representativeness. The NEDC faces critics on not being representative of real driving conditions due to its low acceleration pattern, constant speed cruising phases and high number of idling events, which do not represent transient accelerations regimes [12]. Differences between real world driving cycles and the NEDC can reach between 12% and 30% on fuel consumption and between 32.2 to 628.3% on NO_x over certification figures [12]. Even though it is considered an improvement compared to the NEDC, the WLTP faces critics include the fact that the cycle has slow accelerations, which are not representative of real world driving conditions [5].

Due to these criticisms, the need for performing on-road real driving emission tests has been evaluated by the EC, in order to be incorporated in future assessments of EURO standards. The differences found between laboratorial testing and on-road testing in

emission measurements have highlighted the need to include real driving emission test procedures into the new emissions test standards. As a result, the European Commission will incorporate a Real Driving Emissions (RDE) test procedure for the next EURO standard (monitoring phase starting on 2017, compulsory by 2019 [13]) introducing boundary conditions for the on-road tests and methods for data analysis [3].

EC Regulation (EU) 2016/427 of 10 March 2016 [13] establishes the rules for RDE testing, stating that the vehicle must be tested with a Portable Emissions Measurement System (PEMS), which is a compact equipment composed by a portable gas analyzer, a Global Positioning System (GPS) receiver and a vehicle dynamics data logging system [14]. All these equipment must be integrated and use an acquisition frequency of, at least, 1 Hz [11]. Also, it establishes the requirements for trip selection, which must cover a wide range of real world conditions by accounting with defined shares of urban, suburban (also called as rural) and highway (also called as motorway) operation. Some other parameters considered are trip time, covered distance, ranges of speed, etc. [13]. Ambient boundary conditions are also established by the regulation: maximum and minimum altitude; and temperature for the tests. Table 1 presents a description of ambient conditions and their extended situations. Also, other boundary conditions are present in the regulation, such as vehicle payload and test mass, dynamic conditions and vehicle conditions and operation [13].

Table 1. Vehicles Specifications and Test Conditions [13].

Ambient conditions		
	Minimum	Maximum
Temperature (°C)	0	30
Extended Temperature (°C)	-7	35
Altitude (m)	0	700
Extended Altitude (m)	700	1300

Even with all the referred regulated conditions, RDE tests still have some debatable points that require further detailed study regarding: trip selection; boundary conditions; and data analysis methods. The trip boundary conditions are related with the reproducibility of the test and are mostly correlated with less controlled factors, including environmental conditions, test mass, dynamic conditions, etc. [11]. But, even with all these requirements, reproducibility of RDE tests is hardly achievable and both dynamic and environmental boundaries are unique for a specific geographical location, which can be representative for one location but not for another test-site [15]. Thus, to overcome the reproducibility issue of RDE tests, data analysis methods were introduced for processing test trip data. On-road data analysis methodology is yet to be finally agreed by the EC, in the update of the EURO 6. A more detailed study regarding the methods can be found in the literature [3, 16].

As presented in Table 1, the EU regulation on the external atmospheric temperature set for RDE tests can range from 0°C to around 30°C in normal conditions, which may influence considerably pollutant emissions and energy consumption and opens

the discussion on the cold-start phenomena. In more detail, the cold start phenomenon occurs in ICE powered vehicles before the ICE reaches its most effective operation temperature, affecting both fuel consumption (due to higher heat losses) and pollutant emissions (due to low catalytic converter temperatures). This is an issue related to normal every day operation of a vehicle and a subject of analysis in RDE tests [14, 17]. Therefore, the importance of studying the relations between outdoor temperature and the cold-start duration.

The regulation establishes that the cold-start period covers the first 5 minutes after the initial start of the ICE. In addition, if the coolant temperature can be reliably determined, the cold start period ends once the coolant has reached 70°C for the first time but no later than 5 minutes after initial engine start. The following sections will describe the testing performed and findings on the differences between cold start and warm engine emissions will be presented.

MATERIALS AND METHODS

In this study, two EURO 6 vehicles were tested: one conventional diesel compression-ignition; and one conventional gasoline spark ignition. Both vehicles were tested in three outdoor temperatures ranges (5°C, 10°C and 15°C), in different days. For that purpose, the cars were stored in open parking for at least 12h from one day to another.

The RDE tests were performed following the standard EC RDE test boundaries, including the selection of the trip and environmental conditions. In addition, to reduce the variables and preserve the reproducibility of the tests, the same driver and witness were used as well as the same equipment payload.

Data acquisition was made under on-road conditions in the Lisbon Metropolitan Area, Portugal, with the use of a PEMS collecting on-road data at 1 Hz. In addition, the same route was used for all tests.

EMROAD software provided by the Joint Research Center (EC) (MAW method) [16] was used to analyze each trip and provide a driving category overview regarding the outdoor temperatures and the inclusion of the Cold-Start in the calculations. In addition, the Vehicle Specific Power (VSP) assessment method [10], was also used to analyze the results regarding the coolant temperature and cold-start duration. The input data used was the same for both methods.

Since the MAW method needs WLTP information, which is not yet publicly available for most of the vehicles, an estimate of the certification CO₂ emissions data was obtained with a method previously developed by Duarte et al. [8].

Cold-start has two definitions (first 5 minutes and coolant temperature lower than 70°C) according with EC. This work analyzes the coolant temperature stabilization period for each external temperature range and vehicle in order to explore different approaches for the cold-start accounting on fuel use and emissions.

Consequently, this work aims at comparing two types of propulsion systems in different outdoor temperatures and the respective cold-start period. Thus, it is necessary to briefly understand how the methods work and their mathematic fundamentals as well as the

materials used. In the following sections, a description of the vehicles, of the RDE test conditions, of the used PEMS used, and of the data analysis methods will be presented.

Vehicles Description

The vehicles were tested on the road between one hour and a half and two hours. The main characteristics of the vehicles and their test conditions are summarized in Table 2.

Table 2. Vehicles Specifications and Test Conditions

Vehicles Specifications		
Technology	CI	SI
ICE displacement (L)	1.5	1.5
ICE Power (kW)	78.3	97.7
ICE Torque (Nm)	270	150
Transmission/Gearbox	Manual/6	Manual/6
Vehicle mass (kg)	1575	1215
Power-to-Weight (W/kg)	50	80
Exhaust aftertreatment*	OC+DPF	TWC
Fuel	Diesel	Gasoline
Fuel system	Diesel Commonrail	Direct Injection
Emission Standard	EURO 6	EURO 6
Production Year	2016	2016
Test Conditions		
Altitude (m) (Min/Max)	11/227	7/225
Outdoor Temperature (°C) (Min/Max)	7/17	1/15
Test duration (s) (5°C/10°C/15°C trips)	6484/5538/7143	7787/6511/6334

*OC - Oxidation catalytic converter; DPF - Diesel Particulate Filter;
TWC - Three-way Catalytic Converter

PEMS Description

A PEMS was used to collect data in a second-by-second basis for both vehicles during RDE tests. The information collected included exhaust gas composition, road topography, engine parameters and vehicle dynamics. Moreover, on-road data was acquired by a laptop using developed software that integrates, synchronizes and records the all data at 1 Hz along the trip [14].

Tailpipe gases were continuously measured with a portable gas analyzer, providing information on oxygen (O₂), carbon dioxide (CO₂), carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x). Although exhaust gas flow rates were not measured, the collected data allows estimating ICE fuel consumption and pollutants mass emissions at a 1Hz basis [14].

The vehicle sensors information was also collected using an OBD port reader. The data collected included vehicle speed, engine speed and load, throttle position, manifold absolute pressure, coolant temperature, intake air temperature and airflow mass. In addition, a GPS receiver with integrated barometric altimeter was also used to collect vehicle position and altitude along the trip. Figure 1 shows a diagram of the acquisition system used and its components.

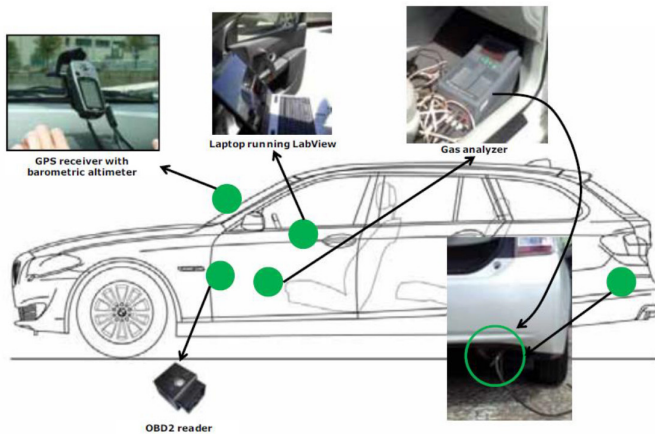


Figure 1. Main components of PEMS installed in light duty vehicles (adapted from [14]).

Data Analysis - Vehicle Specific Power Method

The Vehicle Specific Power (VSP) methodology [10] is a road load model that uses a simplifications of the forces applied on the vehicle, in order to perform an energy and environmental characterization based on the data collected on on-road measurements [11, 18, 26]. Using this methodology, it is possible to estimate the power per mass required under different conditions of speed, acceleration and road grade. Therefore, by combining vehicle dynamics (speed, acceleration, rolling and aerodynamic resistance) (Figure 2) and road grade, it is possible to calculate the correspondent specific power for each point of the trip, in a second by second basis equation 1 [18].

$$VSP = \frac{\frac{d}{dt}(E_{Kinetic} + E_{Potential}) + F_{Rolling} \cdot v + F_{Aerodynamic} \cdot v}{m} \quad (1)$$

One advantage of the VSP methodology is that it is based on typical vehicle inertial, rolling and aerodynamic coefficients, providing a comparison baseline that only accounts for vehicle speed, acceleration and road grade, with little information from vehicle characteristics. This is extremely advantageous since for the same driving power (dynamic) conditions, the energy and environmental performance is only dependent on the propulsion system and vehicle characteristics. However, as observed, VSP considers typical vehicle properties regarding its rolling and aerodynamic resistance, for instance, although it has no significant difference [16]. This approach is in-line with several other studies [11, 13, 19, 20] and can be seen in its final form in equation 2.

$$VSP = v \cdot (1.1 \cdot a + 9.81 \cdot \text{grade} + 0.132) + 3.02 \cdot 10^{-4} \cdot v^3 \quad (2)$$

Where:

- v : Vehicle speed (m/s);
- a : Vehicle acceleration (m/s²);
- grade : Road slope;

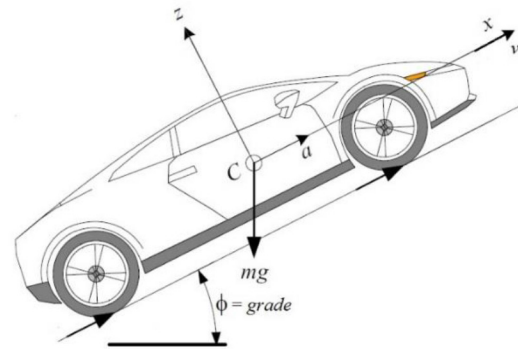


Figure 2. VSP factor at a light duty vehicle (adapted from [17]).

A modal analysis is typically used in VSP methodology to group points with similar power per mass demand (W/kg) and for light-duty vehicles, it is commonly divided in 14 modes [21]. This modal division was set in a way that each mode has statistically different fuel consumption values and none of them is dominant in the estimation of the trip total fuel consumption [8], according to Table 3. On-road data collected allows to assign a fuel use and pollutant emission (in g/s) to each VSP mode, providing an energy and environmental footprint of a given vehicle and propulsion technology.

Table 3. Used VSP Modes and ranges of specific power (W/kg) for each mode [27]

VSP Mode	W/kg	VSP Mode	W/kg
1	$VSP < -2$	8	$13 \leq VSP < 16$
2	$-2 \leq VSP < 0$	9	$16 \leq VSP < 19$
3	$0 \leq VSP < 1$	10	$19 \leq VSP < 23$
4	$1 \leq VSP < 4$	11	$23 \leq VSP < 28$
5	$4 \leq VSP < 7$	12	$28 \leq VSP < 33$
6	$7 \leq VSP < 10$	13	$33 \leq VSP < 39$
7	$10 \leq VSP < 13$	14	$VSP \geq 39$

Note: VSP modes 1 to 2 - Deceleration; 3 - Idle;
4 to 6 - Normal usage low power;
7 to 9 - high power normal usage ;
10 to 14 - High power

After acquiring 1 Hz data from the PEMS system, information on second-by-second fuel use and emissions can be analyzed using the VSP methodology.

Data Analysis - Moving Average Window Method

The Moving Average Window method (MAW), developed by the EU Joint Research Center (JRC) and regulated by EU commission [13], is a method which evaluates RDE using a set of moving average windows. The aim of MAW is to have a reference method to support data analysis from participants in the EU PEMS legislative programs, such as the In-Service Conformity (ISC) for heavy-duty vehicles (HDV) and non-road engines and the Real Driving Emissions (RDE) for light-duty vehicles (LDV) [2]. Thus, according to the EU regulation [13], the MAW method provides an insight on RDE tests with a certain duration and scale. To do that, the test must be divided into sub-sections, also called windows, and subsequent statistical treatment is done focusing at identifying if each window is suitable to assess the vehicle real world behavior or the RDE performance.