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RICARDO

Department of Automotive, Combustion
Engine and Railway Engineering

Potential for Improving Passenger Car Emissions through Analysis of Real Driving Emissions Data

Možnosti snižování emisí automobilu na základě vyhodnocení měření emisí za reálného provozu

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Supervisor:	doc. Michal Vojtíšek, Ph.D.

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Guidelines:

The thesis addresses the potential to reduce exhaust emissions of a passenger car through engine calibration improvements suggested by analysis of real driving emissions (RDE) data. Approximately 10-20 hours of real driving emissions data, along with data recorded during the WLTC driving cycle, are to be analyzed using a suitable data mining tool or analytical package. Modes of operations and combinations of conditions that substantially contribute to the total emissions (short very high emission episodes as well as longer periods of moderately high emissions) will be identified, and potential for emissions reduction explored. Applicability of the findings to other engines and automated calibration procedures is to be discussed. Relevant background on engine and exhaust aftertreatment technology and emissions testing should be summarized.

Bibliography / sources:

SUAREZ-BERTOA, Ricardo, et al. On-road emissions of passenger cars beyond the boundary conditions of the real-driving emissions test. Environmental research, 2019, 176: 108572.
HOOFTMAN, Nils, et al. A review of the European passenger car regulations–Real driving emissions vs local air quality. Renewable and Sustainable Energy Reviews, 2018, 86: 1-21.
LEE, Sung-Yong, et al. Hardware-in-the-Loop-Based Virtual Calibration Approach to Meet Real Driving Emissions Requirements. SAE International Journal of Engines, 2018, 11.2018-01-0869: 1479-1504.

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Abstract

In this thesis, relevant background on emissions, engines, aftertreatment technology is summarized and introduction into emissions data analysis and calibration is presented. The importance of involving the real driving emissions (RDE) procedure into the emissions testing process was emphasized based on differences between Worldwide harmonized Light duty Test Cycle and RDE test. RDE Data Analysis through Ricardo RDE Data Mining Tool was performed and the risk areas in terms of emissions testing were identified. Based on the analysis, cold start was examined in more detail with a particular focus on its impact on the RDE urban part. Afterwards, absolute emissions analysis was carried out in order to find the periods that contributed the most to the overall emissions. The very beginning of a drive and catalyst heating mode were identified as having the greatest potential to improve the emissions of passenger cars. The most reasonable solutions, e.g. electrically heated catalyst were explored.

Abstrakt

V této práci jsou shrnuty základy motorů, prvků výfukového systému, emisí a obsahuje úvod do analýzy emisních dat a kalibrace. Na rozdílech mezi WLTC (Worldwide harmonized Light duty Test Cycle) a RDE (real driving emissions) je prezentována důležitost zahrnutí RDE testů do emisního testování. Pomocí Ricardo RDE Data Mining Tool byla provedena analýza RDE dat a byly identifikovány rizikové oblasti z hlediska aktuálních emisních limitů. Na základě této analýzy se práce zaměřila na studený start, a především na to, v jakém rozsahu se promítá do výsledků městské části RDE testu. Následně byly analyzovány absolutní hodnoty emisí za účelem nalezení provozních režimů a kombinací podmínek, které nejvíce přispívají k vyšším celkovým emisím. Na základě vyhodnocovaných dat má největší potenciál ke zlepšení emisí automobilu optimalizace úplného začátku testu/jízdy a mód vyhřívání katalyzátoru. Dále jsou popsána nejvhodnější řešení této problematiky, jako např. elektricky vyhřívaný katalyzátor.

Declaration

I hereby declare that I am the sole author of this bachelor's thesis and that, to the best of my knowledge and belief, I have not used any sources other than those listed in the bibliography and identified as references. I further declare that I have not submitted this thesis at any other institution in order to obtain a degree.

In Prague: ……………………………………………

……………………………………………

Marek Fencl

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I would first like to thank my supervisor doc. Michal Vojtíšek, Ph.D. at the CTU Prague for his guidance and advice throughout this thesis and for sharing valuable insights from his scientific field.

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Finally, I must express my gratitude to my family for their support and continuous encouragement throughout my years of study. Thank you.

Marek Fencl

Contents

List of Acronyms

AFR......... Air-to-fuel ratio

CF........... Conformity factor

CI............ Compression ignition

CO........... Carbon monoxide

CO_2.......... Carbon dioxide

DPF......... Diesel particulate filter

EC........... European Commission

ECU......... Engine control unit

EGR......... Exhaust gas recirculation

EHC......... Electrically heated catalyst

EU........... European Union

GDI.......... Gasoline direct injection

GPF......... Gasoline particulate filter (cGPF – coated)

H_2O......... Water

HC........... Hydrocarbon

HDV........ Heavy duty vehicle

HEV......... Hybrid electric vehicle

ICE........... Internal combustion engine

ISC.......... In-service conformity

MAW....... Moving averaging window

N_2............ Nitrogen

NEDC...... New European driving cycle

NMHC..... Non-methane hydrocarbons

NO........... Nitrogen monoxide

NO_2......... Nitrogen dioxide

NOx........ Nitrogen oxides

N_2O......... Nitrous oxide

NTE......... Not to exceed

O_2........... Oxygen

O_3........... Ozone

PEMS...... Portable emissions measurement system

PFI........... Port fuel injection

PM........... Particulate matter

PMR........ Power-to-mass ratio

OEM........ Original equipment manufacturer

PN........... Particle number

RDE......... Real driving emissions

RNS......... Reactive nitrogen species

SI............ Spark ignition

TA........... Type approval

TDC......... Top dead center

(BTDC – before)

THC......... Total hydrocarbon

TWC........ Three-way catalyst

LDV......... Light duty vehicle

WHO....... World Health Organization

WLTC...... Worldwide harmonized Light duty Test Cycle

WLTP...... Worldwide harmonized Light duty Test Procedure

1 Introduction

Passenger cars with internal combustion engine (ICE) have become an important part of our society in the last century and nowadays, they represent much more than just a mean of transport. They have become a symbol of social status, have their own sport industry and play important role in culture as well as in entertainment. There is not that many other mass-produced products, that would affect our society in such extent. As standard of living increases, so does the number of passenger cars worldwide.

However, passenger cars are an important source of air pollution, especially in urban areas, where large number of people are directly exposed. Poor air quality is an important environmental health hazard, resulting in health problems for the population and high costs for health care systems [1]. More than 95 % of the European population living in urban areas is exposed to ambient air concentration levels of particle matter (PM), nitrogen oxides (NOx) or ozone (O_3) that are deemed unsafe by the World Health Organization (WHO) [1].

Due to the enormous amount of invested resources and efforts, the pollutant content of the exhaust gases has been reduced to fractions of percentage of the original values over the past forty years. However, as traveling by car has become more and more affordable, the efficiency of utilizing cars has unfortunately worsened. Usual user approach to a machine is to utilize it to a full extent in order for it to valorize itself, which is not the case for majority of cars today. [2]

Recently, real-driving emissions (RDE) test procedures have been introduced in the EU aiming to evaluate nitrogen oxides (NOx) and particulate number (PN) emissions from passenger cars during on-road operation [3]. This increases the demand for better, more sophisticated construction, innovative engine and aftertreatment technologies and accurate engine control with its calibration.

2 Emissions

As the number of vehicles increases, the need to lower the air pollution grows. Airborne pollutants such as gases, chemicals and smoke particles emissions of exhaust gases, being products of combustion of fossil fuels, are causing significant health and environmental problems. In developed countries and especially in cities, exhaust gases of passenger cars are a substantial part of pollution caused by man. [2]

Most vehicles nowadays are equipped with ICEs (will be discussed in the following parts), in which a mixture of hydrocarbons is burned. Ideal combustion can be described by following simplified equation 1. [4]

$$\text{HC (fuel)} + O_2 \text{ (air)} \rightarrow CO_2 + H_2O + \text{energy} \tag{1}$$

The main products are water (vaporized) and carbon dioxide. However, in real conditions, many combustion by-products are formed within the combustion chamber. Many of them are harmful and their maximums are therefore regulated by legislation.

2.1 The Most Relevant Pollutants

The combustion of petrol and diesel fuels is a known source of airborne pollutants such as carbon monoxide, nitrogen oxides, sulfur dioxide, particulate matter, benzene and polycyclic aromatic hydrocarbons [5]. The most relevant and discussed pollutants are further specified below.

2.1.1 Carbon monoxide (CO)

CO is a colorless, odorless poisonous gas that is a product of the incomplete combustion of hydrocarbon-based fuels. Increased amount of CO is emitted especially as a result of combustion of a rich air/fuel mixture (will be discussed in the following). The method by which CO is formed is shown in equation 2.

$$\text{HC} + \text{insufficient } O_2 \rightarrow CO_2 + CO + H_2O \tag{2}$$

CO binds to the hemoglobin contained in blood over two hundred times more avidly than oxygen; thus prevents the release of any remaining oxygen to the body tissues, effectively poisoning by suffocation. [5]

2.1.2 Nitrogen oxides (NOx)

NOx is the generic term for a group of highly reactive colorless and odorless gases that contain varying amounts of nitrogen and oxygen. When referring to

NOx, the talk is mainly about its two most abundant oxides – NO and NO_2 (others are for example reactive nitrogen species – RNS). The main mechanism for the formation of NOx involves the oxidation of atmospheric nitrogen under the high pressure and temperature conditions that occur in an ICE. [5]

Next to traffic as a primary NO_2 source, secondary NO_2 is formed atmospherically under the influence of sunlight, the presence of nitrogen monoxide (NO) and ground-level ozone (O_3). This chemical reaction is responsible for approximately 70 % of the NO_2 measured in cities. For these reasons, the NOx gases are considered as the primary pollutant. [6]

2.1.3 Particulate Matter (PM)

PM refers to a complex mixture of different small particles and liquid droplets. PM is particularly a product of combustion in lower temperatures and its main source are areas in combustion chamber with rich local air/fuel mixtures ($\lambda < 0{,}6$) [2]. More PM is for these reasons emitted by CI engines and by SI engines with direct injection (will be discussed in following parts).

The particle size is the key characteristic that relates to the toxicity of airborne PM. Coarse particles have little effect to health, whereas fine particles are deposited in the smallest passages (Bronchioles) within the lungs. [5]

2.1.4 Hydrocarbons (HC), Carbon Dioxide (CO_2) and Others

Unburned hydrocarbons (volatile organic compounds) consist from unburned fuel and oil. Gaseous hydrocarbons are a complex mixture and it is determined by the conditions in the combustion chamber. They are usually measured as total hydrocarbon (THC) because measurement of the separate gases would be costly.

As a product of perfect combustion, CO_2 is now considered a pollutant due to its classification as a “greenhouse gas” and its contribution to global warming. [5]

Although ICEs, and diesel particularly, have come under significant emissions pressure, much of this seems misplaced. ICEs can have negative emissions, wherein the tailpipe has lower pollution levels than the ambient air. We have known this for PN emissions from DPFs since their commercial introduction [7]. This is true for certain conditions and for PN emissions only. Nevertheless, for most cases they can be considered correct.

At this point, it is important to be aware of the difference between “greenhouse” gases, which contribute to global warming (such as CO_2 or N_2O), and health relevant pollutants (such as NOx). Both types of emissions must be regulated.

3 Engines and Emissions Reduction Technology

3.1 Engine Basics

The ICE is one of the few inventions that, since its inception, has affected virtually the entire population of the globe. An internal combustion engine is a heat engine, in which an exothermic reaction is made to occur by the controlled ignition of a fuel with an oxidizer, leading to the formation of gases of high temperature and pressure. In an internal combustion engine, the gaseous combustion products are permitted to expand, and in doing so carry out useful work by acting directly to cause movement (usually the movement of a piston within an enclosed cylinder). [5]

ICEs can be broadly split up into two groups:

- Spark ignition (SI) engines in which a compressed air-fuel charge within the engine cylinder is ignited by a suitable energy source (typically a spark plug).
- Compression ignition (CI) engines in which the fuel ignites inside the engine cylinder because of the chemical kinetics of an increase in pressure and temperature caused by a tight-fitting piston compressing the air-fuel charge within the cylinder. [5]

Fig. 1 displays a schematic of a modem ICE, with labels pointing out components of interest.

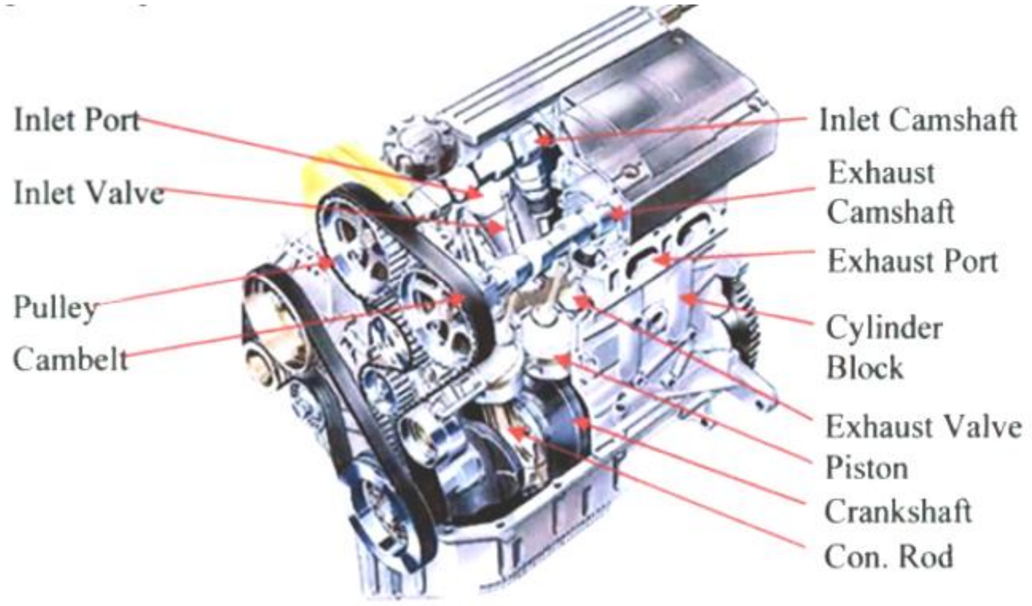


Fig. 1 – Internal combustion engine schematic [5]

3.2 Rich and Lean Air/Fuel Mixture

Petrol has an approximate composition of 15 % hydrogen and 85 % carbon by mass. The oxygen for combustion is contained in the air supply and approximately 15 kg of air contains the amount of oxygen that will ensure complete combustion of 1 kg of petrol. This means that the air-to-fuel ratio (AFR) for complete combustion of petrol is approximately 15:1; a more precise figure is 14.7:1 [8]. When there is precisely enough air in a fuel/air mixture for complete combustion to occur, the mixture is said to be stoichiometric. If there is too much air the mixture is described as fuel "lean" and conversely if there is insufficient air the mixture is described as fuel "rich". [5]

Generally, SI engines tend to run on slightly rich mixtures in order to better balance exhaust emissions. The AFR calibration is one of the most important "playgrounds" for a calibration engineer.

To describe a fuel mixture, so called air-fuel equivalence ratio or λ (lambda) is widely used and defined as:

$$\lambda = \frac{AFR}{AFR_{stoich}} \tag{3}$$

or fuel-air equivalence ratio ϕ, which is simply defined as:

$$\Phi = \frac{1}{\lambda}. \tag{4}$$

Influence of air/fuel mixture composition on the emission compounds concentrations of a gasoline engine in shown in Fig. 2.

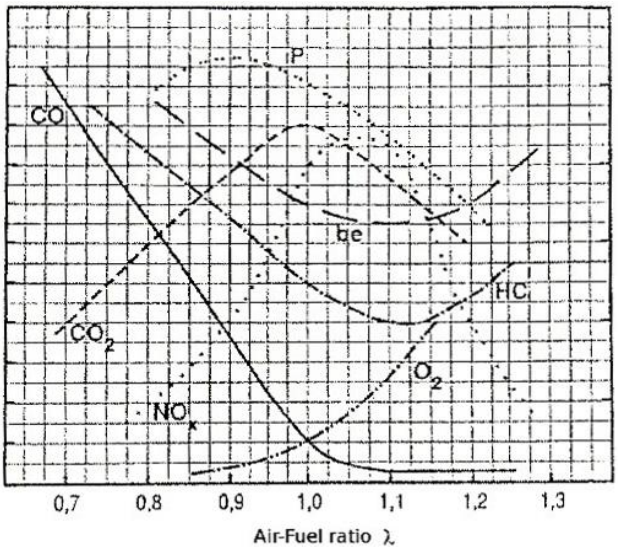


Fig. 2 – Influence of air/fuel mixture composition on the parameters (emission compounds concentrations, specific fuel consumption be, specific power output p) of a gasoline engine [9]

3.3 Domains of SI and CI Engines

The quantity and composition of exhaust gases from an ICE depends the most on its type (SI/CI). This is due to the differences in combustion process and different fuels (diesel contains “heavier” hydrocarbons than gasoline). There are obviously many other aspects that influence the engine emissions, such as engine displacement, ECU calibration, turbocharging, exhaust gas recirculation (EGR), weight of the vehicle, road load terms, tires etc.

3.3.1 Spark Ignition Engines

Vast majority of SI engines is mostly operated at stoichiometric air to fuel ratio. The ration of the charge is controlled by one or more λ sensors, which measure a partial pressure of O_2 in exhaust gases. This kind of combustion leads to a higher fuel consumption, higher raw emissions (engine-out emissions before entering aftertreatment) and higher temperatures in combustion chamber compared to CI engines. However, the higher temperatures contribute to lower PM emissions and the stoichiometric mixture facilitates subsequent catalytic processes in the three-way catalyst (TWC). [2]

3.3.2 Compression Ignition Engines

CI engines have become popular in LD vehicles due to lower fuel consumption compared to gasoline engines. This advantage is a consequence of operating the engine at lean fuel mixtures and higher compression ratios. Combustion of lean mixtures leads to lower temperatures in combustion chamber and higher volume flow of exhaust gases compared to SI engines. The surplus of air (and thus oxygen as well) in the air/fuel mixture cause significantly lower CO and HC emissions. Due to lower temperatures and diffusion flame occurring in the chamber, the production of NOx is decreased. However, the lower temperature leads to higher production of soot (PM). The air surplus in air/fuel mixture limits a direct NOx reduction, resulting in more complicated and more sophisticated catalytic systems. [2]

Coupled with incremental advances in the diesel engine and aftertreatment technology, LD diesels continue to offer a very competitive option for meeting upcoming CO_2 standards. Focus is on improving NOx emissions, especially under low temperature associated with slow urban driving. [7]

As the object of this thesis is to analyze emission data for a vehicle with SI engine, only technology used mainly with gasoline engines will be described.

3.4 Injection Types

Gasoline direct injection (GDI) engines have become the preferred standard for gasoline light-duty vehicles in the worldwide market, replacing Port fuel injection (PFI) engines. They have been developed by many modern engine manufacturers to take advantage of the increase in engine efficiency and the reduction in emissions. [10]

Direct fuel injection is a recent development in petrol engines but has been used in diesel engines for many years. The injection of the fuel at high pressure directly into the combustion chamber moments before the spark plugs fire allows the precise control of the stratified charge required for engines to operate with lean air/fuel mixtures [5]. However, GDI engines, similarly to CI engines, tend to emit more soot (PM) than PFI engines.

3.5 Exhaust Gas Recirculation

The recirculation of exhaust gas back into the combustion chamber can result in reduction of engine's fuel consumption and especially its NOx emissions. EGR works by recirculating up to 10 % of the exhaust gas back into the cylinder via are circulation valve controlled by the ECU, which effectively reduces the engine's displacement and pumping losses. [5]

The basic principle of EGR is shown in Fig. 3.

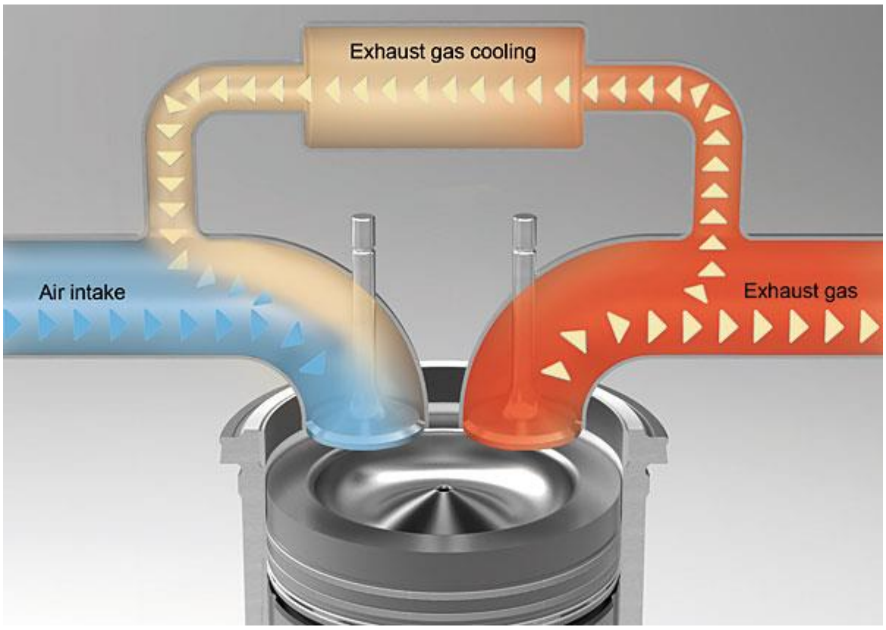


Fig. 3 – Exhaust gas recirculation principle [11]

The air that is used to provide the oxygen for combustion contains approximately 77 % nitrogen by mass. When nitrogen is heated above approximately 1 800 °K (1 527 °C), in the presence of oxygen, NO is formed and it is than partially converted into NO_2. These conditions occur in the combustion chamber when excess oxygen is present as happens at an air–fuel ratio of approximately 16:1. If the combustion chamber temperature is kept below 1800 °K, the conditions for the creation of NOx no longer exist. Exhaust gas recirculation is a method that is used to keep combustion chamber temperatures below the critical figure. [8]

3.6 Aftertreatment Technology

To satisfy the growing demand in fuel consumption and emissions characteristics, ICEs underwent a rapid development in the past 20 years. Their operation became quieter, the specific power output nearly doubled thanks to the advancements in supercharging and injection technology, the exhaust gases are cleaner due to utilization of advanced (and expensive) aftertreatment solutions and the fuel consumption dropped [12]. The treatment of an engine's exhaust gases to reduce the emission content is an increasingly important method used by engine manufacturers to meet the stringent legislation. [5]

As the object of this thesis is to analyze emission data for a vehicle with SI engine, only the aftertreatment of vehicle with gasoline engine (Fig. 4) is closer described in the following.

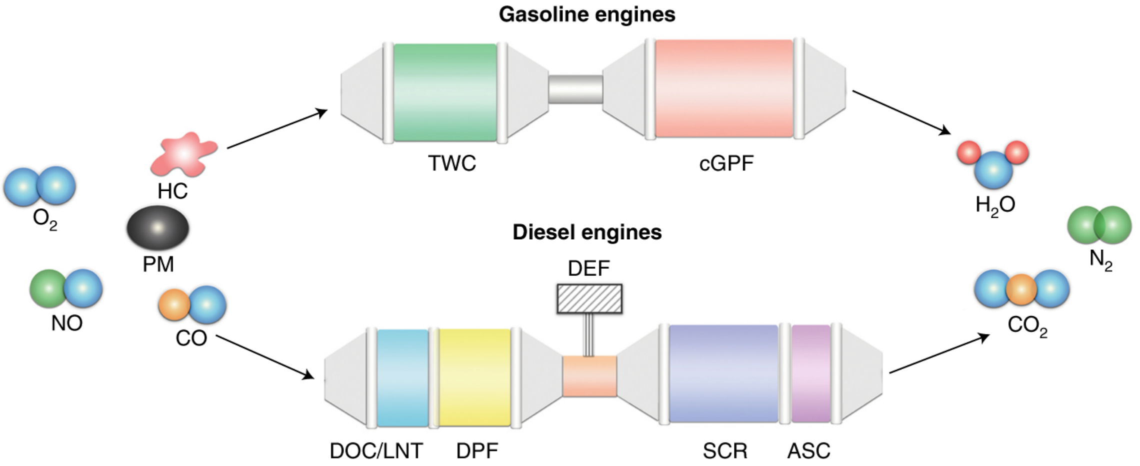


Fig. 4 – Two typical configurations of modern gasoline (top) and diesel (bottom) emission control systems [13]

3.6.1 Three-Way Catalyst

In general, catalysts are materials that assist chemical reactions but are not themselves changed in the process. The TWC, shown schematically in Fig. 5, is generally a multicomponent material, containing the precious metals like rhodium and platinum. It typically consists of a ceramic monolith with strong porous walls enclosing an array of parallel channels [14].

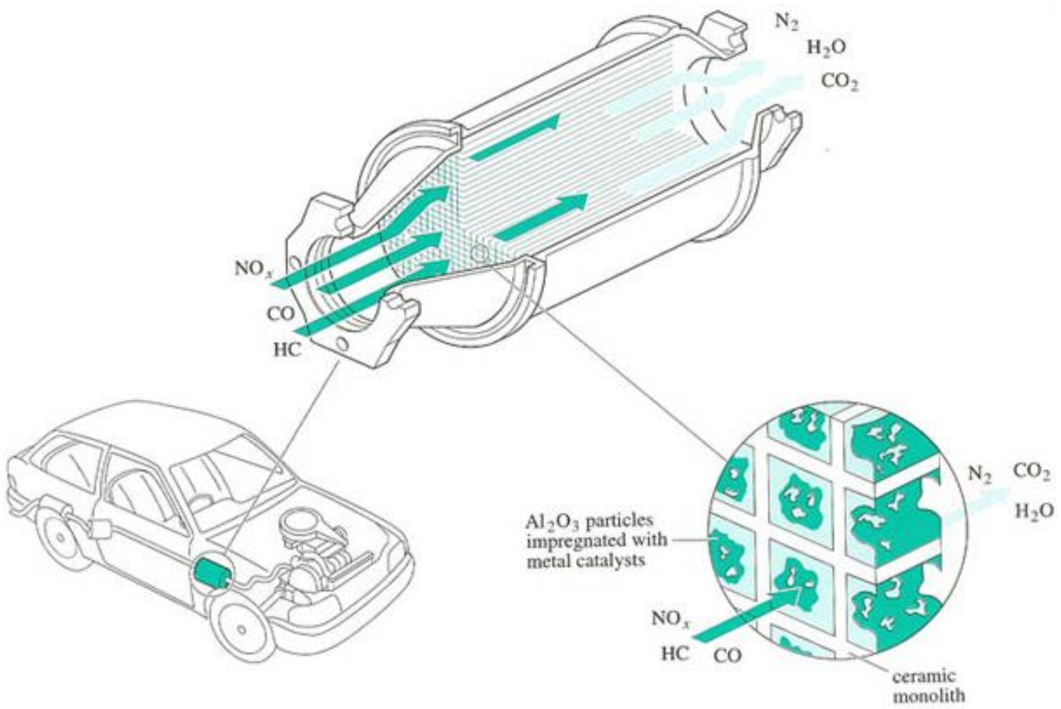


Fig. 5 – Three-way catalyst [14]

A three-way catalyst (TWC) oxidizes exhaust gas pollutants - both hydrocarbons (HC) and carbon monoxide (CO) – and reduces nitrogen oxides (NOx) into the harmless components – water (H_2O), nitrogen (N_2) and carbon dioxide (CO_2). [15]

At the correct temperature, in excess of 300 °C, platinum acts as a catalyst that aids the conversion of CO to CO_2, and HC to H_2O and CO_2. Rhodium is a catalyst that reduces NOx to N_2. These metals are added to a ceramic honeycomb structure that exposes the exhaust gases to the maximum area of the catalyzing material. [8]

Depending on the operating conditions of the engine and the exhaust gas composition, conversion rates of close to 100 % can be achieved at close to stoichiometric (lambda equal 1) conditions (see Fig. 6). The necessary reaction conditions can be reached after less than a minute by the introduction of special cold-start measures, especially a fast heat-up of the exhaust gas after engine cranking. This is especially important for city driving, characterized by frequent start-stop events. [15]

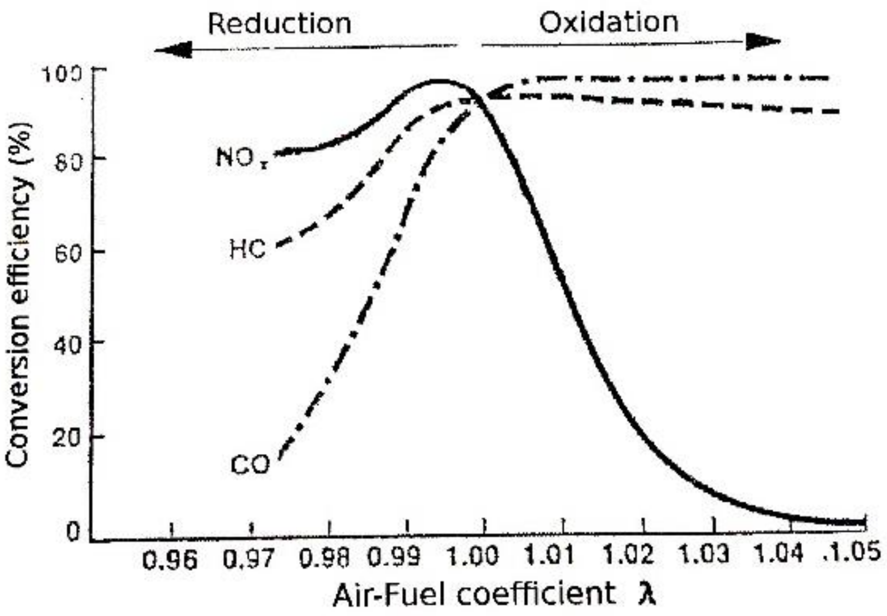


Fig. 6 – Elimination efficiency of a TWC in dependence on λ for various chemical components [9]

3.6.2 Gasoline Particulate Filter

With newest legislations in Europe and China requiring compliance with a particle number (PN) limit of $6 \cdot 10^{11}$ #/km, particulate filters are applied to gasoline engines. [16]

Gasoline particulate filters (GPF) are an emission aftertreatment technology based on diesel particulate filters (DPF), developed to control particulate emissions from GDI engines. [17]

Filter substrates for gasoline engines are typically made of cordierite. Compared to a DPF the particle size distribution in gasoline exhaust is different (shifted to smaller particles) and the maximum operation temperature is typically higher for a GPF. This higher temperature also allows an easier regeneration of the filter compared to diesel. [16]

Most early GPF applications included an uncoated GPF positioned downstream of a TWC catalyst. As the technology matured, GPFs have been also coated with a three-way catalyst. This catalyst coated GPF (cGPF) configuration is sometimes referred to as the 4-way catalyst. [17]

4 EU Legislation & Emissions Testing

Efforts to protect the environment have led to the introduction of emissions standards in all developed countries. The pioneers in this area were the United States of America, especially the state of California. All the emissions tests are designed to regulate the amount of toxic exhaust gases of a vehicle under specified operating conditions. However, the ways of operating a vehicle and using habits vary according to the specific conditions for given location. Therefore, several emissions standards have been developed depending on the geopolitical location (see Fig. 7), although the current trend is to gradually unify these standards. [2]

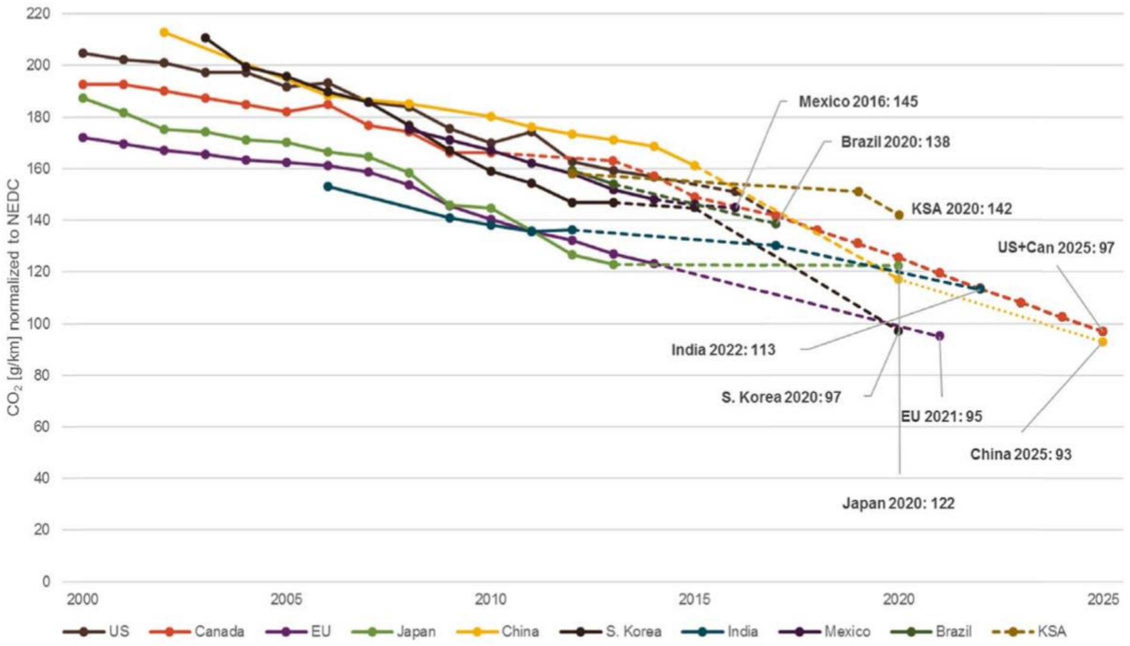


Fig. 7 – An overview of the various CO_2 emission targets in NEDC-equivalents [6]

With the aim of harmonizing emissions testing worldwide, the United Nations' World Forum for the Harmonization of Vehicle Regulations launched a project in 2007 to develop the Worldwide harmonized Light duty Test Procedure (WLTP) and Test Cycle (WLTC). [6]

In Europe, the European Commission's strategy for low-emission mobility aims to limit transport-related greenhouse gas emissions by 2050 to be at least 60 % lower than in 1990. In line with the strategy, the Commission adopted a legislative proposal in late 2017, targeting reductions in average fleet CO_2 emissions from new LD vehicles. [7]

Once again, it is important to be aware of the difference between "greenhouse" gases, which contribute to global warming (such as CO_2, N_2O or methane), and health relevant pollutants (such as NOx). Both types of emissions must be regulated.

4.1 Situation in Europe/Background

Relatively higher fuel taxes in Europe are the reason why 60 % less fuel is used per capita compared to the U.S. [6]. Therefore, European consumers had been demanding fuel efficiency over other aspects of operating a vehicle – for example emissions.

EU regulators had allowed fuel efficient diesel cars an exceedance of 2,1 times the 80 mg/km NOx emissions limit until 2020. By the same year, all passenger cars and light trucks in the U.S. should comply with combined limit of 40 mg/km for non-methane organic gasses and NOx. This is one of the major reasons why diesel technology only started to get a foothold in the U.S. light-duty [6]

Europe's regulation of passenger car emissions (based on NEDC test cycle) has been proven to have failed when it comes to nitrogen oxide emissions (NOx) by diesel engines. Due to historical decisions favoring diesel technology and relatively low emissions (except PM) of CI engines compared to SI engine without any aftertreatment technology available, Europe has become a diesel island with no equal worldwide. [6]

With the introduction of the WLTP, the EC hopes that an end – or at least a significant reduction – will come to the significant differences between the legislative limits and the amount of emissions in reality. [6]

It is an example of how political decisions shape the industry and vice versa. Anon-technical adverse effect of high diesel shares is the external cost to society due to the induced health care costs. [6]

4.2 EU Legislation

European emission regulations are known as a series of regulations (see Fig. 8) that have entered into force consecutively starting with Euro 1 in 1992 to Euro 6d (Euro 6d came into force recently).

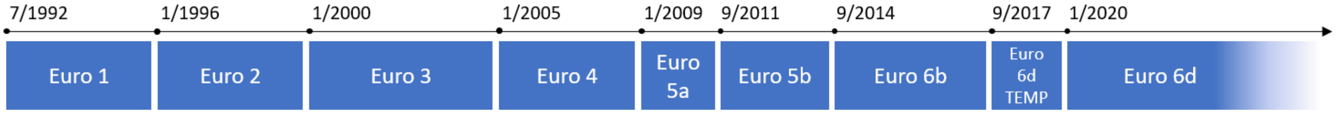


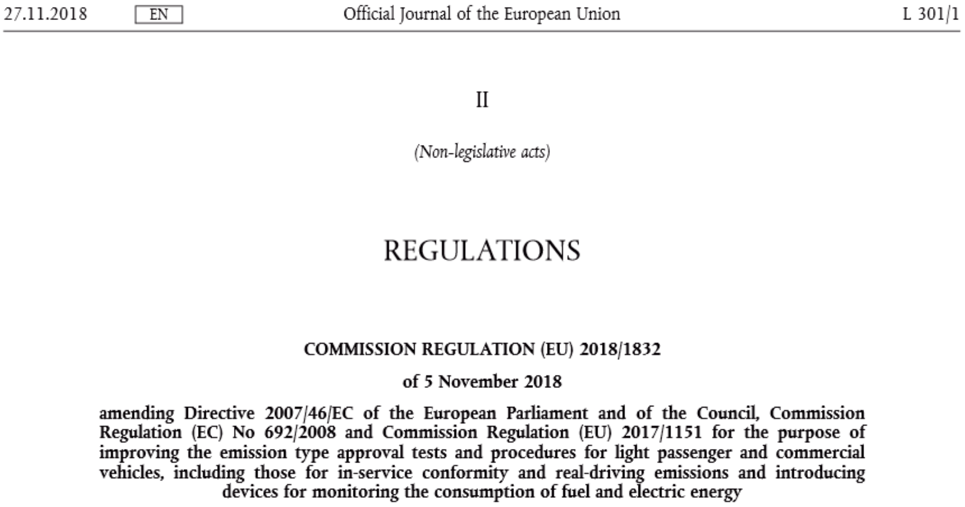
Fig. 8 – EU emissions standards timeline (adapted from [18])

The amount of toxic exhaust gases of a vehicle under specified operating conditions is regulated and tested in specially designed procedure. Emissions are expressed in g/km (except PN, which is expressed in #/km). Euro 6d Limits applicable to passenger cars capable of carrying up to 9 persons and weight up to 2 610 kilograms (M1 category) are shown in Table 1. The Euro 6d is applicable for all new type approvals from January 1st, 2020 and for all new first registrations (previously type approved) from January 1st, 2021. [19]

Table 1 – Euro 6d, M1 category emissions limits [19]

Engine type	CO *[g/km]*	NOx *[g/km]*	PN *[#/km]*	PM *[g/km]*	HC+NOx *[g/km]*	THC *[g/km]*	NMHC *[g/km]*
SI Engines	1	0,06	$6 \cdot 10^{11}$	0,0045	-	0,1	0,068
CI Engines	0,5	0,08	$6 \cdot 10^{11}$	0,0045	0,17	-	-

The following parts are a summary of the newest EU 2018/1832 regulation from 5th November 2018 (Fig. 9). It does not represent the whole document and points out the relevant information for this thesis only.



27.11.2018 EN Official Journal of the European Union L 301/1

II

(Non-legislative acts)

REGULATIONS

COMMISSION REGULATION (EU) 2018/1832

of 5 November 2018

amending Directive 2007/46/EC of the European Parliament and of the Council, Commission Regulation (EC) No 692/2008 and Commission Regulation (EU) 2017/1151 for the purpose of improving the emission type approval tests and procedures for light passenger and commercial vehicles, including those for in-service conformity and real-driving emissions and introducing devices for monitoring the consumption of fuel and electric energy

Fig. 9 – EU 2018/1832 regulation [19]

4.3 Worldwide Harmonized Light Duty Test Procedure (WLTP)

In order to narrow the gap between laboratory emissions and real-world emissions, the Worldwide harmonized Light duty Test Procedure (WLTP) and the RDE test procedures – the latter using Portable Emissions Measurement Systems (PEMS) have been introduced in the EU 2017/1151 an further updated in EU 2018/1832 [3]. These tests were devised to be more representative of real-world driving conditions than NEDC (New European Driving Cycle), which has been the only standardized homologation procedure before.

Since September 2018, all vehicles must be certified according to the WLTP test procedure [18] and its two main parts – WLTC and RDE testing – are to be described.

4.4 Worldwide Harmonized Light Duty Test Cycle (WLTC)

Both NEDC and WLTC are tests conducted in laboratory conditions, on chassis dynamometer (see Fig. 10), which simulates passive resistance and road load terms of the vehicle. Test driver must follow a certain speed profile, which is strictly defined to make the tests comparable.

Fig. 10 – Photo of a chassis dynamometer [2]

Based on real driving data, WLTC should be more realistic that the NEDC. The WLTC cycle is longer (30 minutes instead of 20 minutes) and contains more high-speed driving and less vehicle stops (see Fig. 11). The acceleration is harder and the cycle in general is more dynamic.

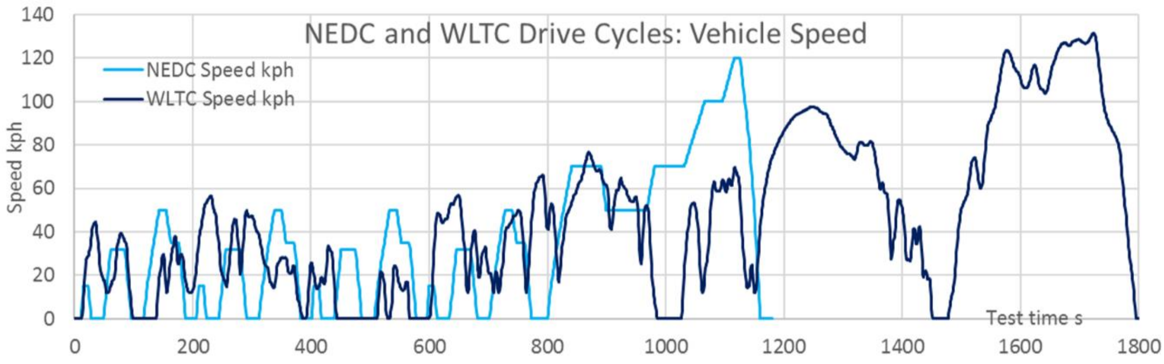


Fig. 11 – NEDC and WLTC vehicle speed comparison [20]

The defined vehicle speed profile during WLTC cycle depends on the power-to-mass ratio (PMR) of the vehicle and maximum speed declared by OEM (Original equipment manufacturer). WLTC Class 3b is relevant for the majority of vehicles (with PMR > 34 and v_{max} > 120 km/h).

4.5 RDE Testing

Real Driving Emissions (RDE) testing requirements are being phased in since September 2017 as part of the WLTP to control vehicle emissions under real driving conditions. The reason for this is that real driving conditions have been shown to give different (in some cases significantly different) emissions levels to the certification tests in the laboratory. [20]

Being an on-road test subject to variability in several factors (ambient conditions, driver's behavior, payload, etc.), RDE accounts for a larger variety of real-world driving situations covering a 'normal driving' testing space [3]. Each test has different vehicle speed profile (see Fig. 12). The trip must include 3 portions: urban; rural and highway in that order.

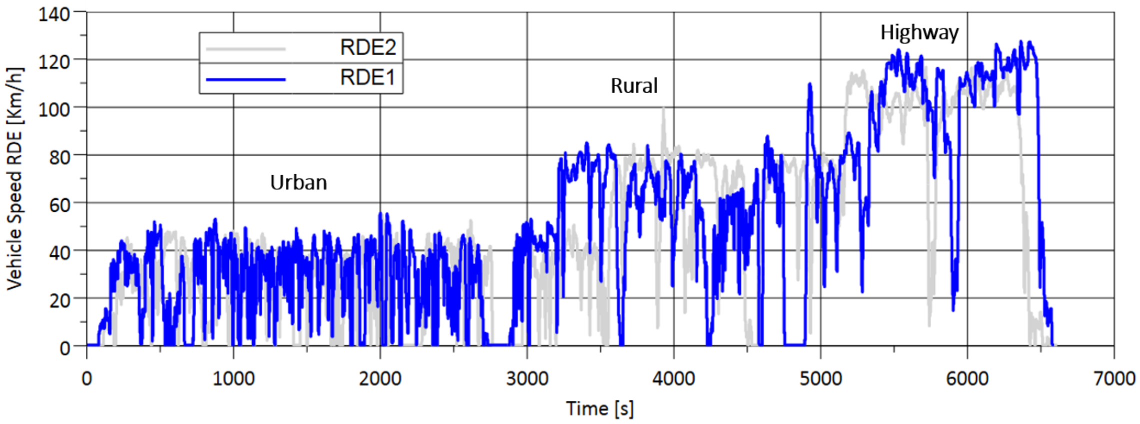


Fig. 12 – Different RDE tests with different vehicle speed profiles

The RDE test is intended to comply with "not-to-exceed" emissions limits, to complement the certification cycle, and apply to all light-duty vehicles. The test trip requirements (see Table 2) and boundary conditions (see Table 3) were developed from various sources, including the database used to generate the WLTC, in order to avoid "abnormal" driving, but still allow a broad range of environmental conditions and driving styles in which the vehicle emissions must remain compliant. [20]

Table 2 – Trip requirements for a valid RDE test (adapted from [18])

Trip requirements for a valid RDE test			
Driving portion	Urban	Rural	Highway
Vehicle speed	Spd ≤ 60 km/h	60 < Spd ≤ 90 km/h	90 km/h < Spd
Minimum distance	16 km	16 km	16 km
Distance share	29-44 %	23-43 %	23-43 %
Total trip duration	90-120 minutes		
Average speed including stops	15 < Avg < 40 km/h	-	-
Total stop time (v < 1 km/h)	6-30 % time	-	-
Individual stop time	≤ 300 sec	-	-
v > 100 km/h	-	-	≥ 5 min
v < 145 km/h	-	-	≤ 3 % time
Cumulative positive elevation gain	< 1200 m / 100 km		
Start/end test elevation difference	≤ 100 m		

The ambient conditions (see Table 3) become extended when the temperature or altitude conditions are extended. If the ambient conditions are extended during a particular time interval, the corrective factor shall be applied to the emissions during this time interval before being evaluated.

Table 3 – Boundary conditions of a valid RDE trip (adapted from [18])

Ambient condition	Moderate	Extended
Emissions corrective factor	1	1,6
Temperature	0 ≤ T ≤ 30°C	-7 ≤ T < 0°C; 30 < T ≤ 35°C
Altitude	≤ 700 m	700 < Alt < 1300 m

Portable Emissions Measurement System (PEMS) – see Fig. 13 – was developed to enable on-road testing.

Fig. 13 – PEMS device installed on a test vehicle [21]

The regulations have been introduced progressively, within 4 RDE "packages" amending the base regulation (see Fig. 14). The RDE regulation is applicable to all new types since September 1st, 2017 and to all new vehicles since September 1st, 2018 (The last 4th package refined the regulation and came into force on 1st January 2019). [19]

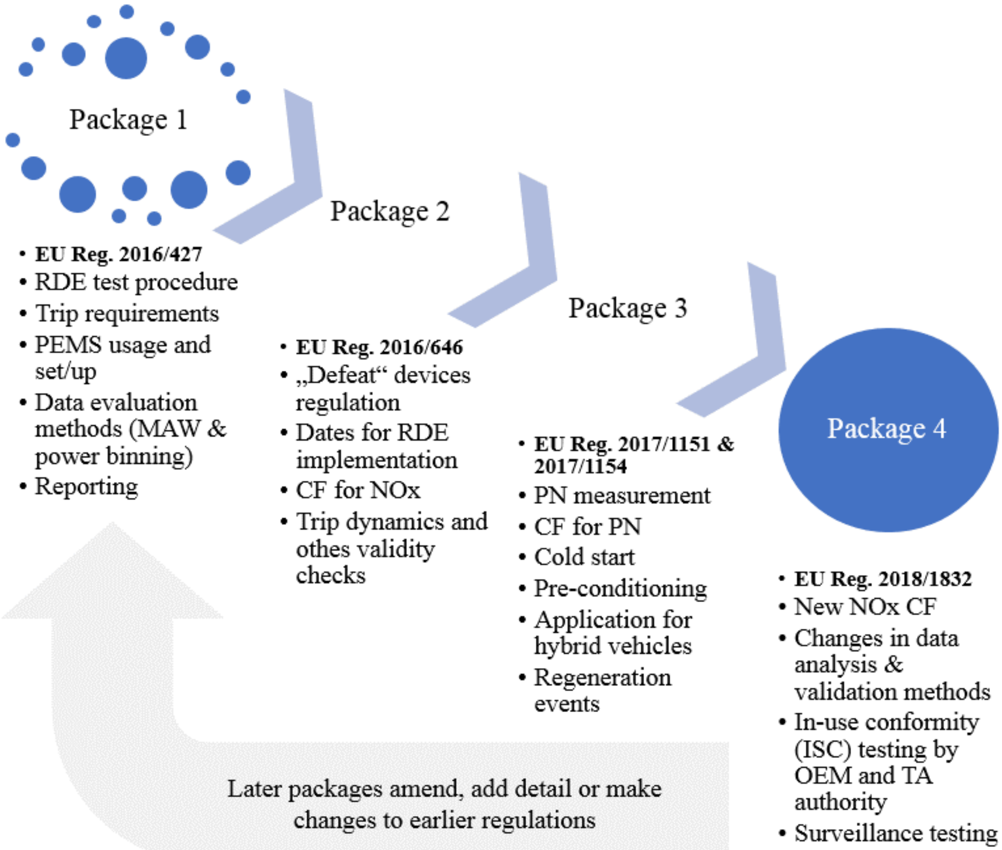


Fig. 14 – Introduction of RDE packages (amendments)

The 4th package with in-use conformity testing and surveillance testing demonstrates the principle that any vehicle may be tested by anyone over any (valid) driven RDE route, and still be compliant. Vehicles (M1 category) need to show compliance with their emission limits throughout their normal life (5 years or 150 000 km, whichever is sooner) under normal conditions of use. [3]

4.5.1 Conformity Factor

For the automotive industry to be allowed sufficient lead-time to adapt their strategies, a two-phase approach was implemented to bring down the RDE NOx and PN emissions. Instead of imposing compliance with the actual limits, conformity factors (CF) – or multipliers – were introduced. [6]

$$CF = \frac{RDE\ Test\ Result\ g/km}{Legislated\ Limit\ g/km} \tag{5}$$

Based on an amendment done in 4th RDE package, a NOx conformity factor of 1,43 is applicable for all new types and all new vehicles from January 1st, 2020 and January 1st, 2021, respectively. This conformity factor requires full compliance with the Euro 6 emission limits (i.e., a conformity factor of 1), but allows a margin of 0,43 to account for the additional measurement uncertainty of PEMS relative to standard laboratory equipment. The margin for PN was set to 0,5 (CF_{PN} = 1,5) in 3rd RDE package and it is applicable since September 1st, 2018 for all new vehicles. [3] Fig. 15 illustrates how the diesel NOx emissions limits evolved throughout time.

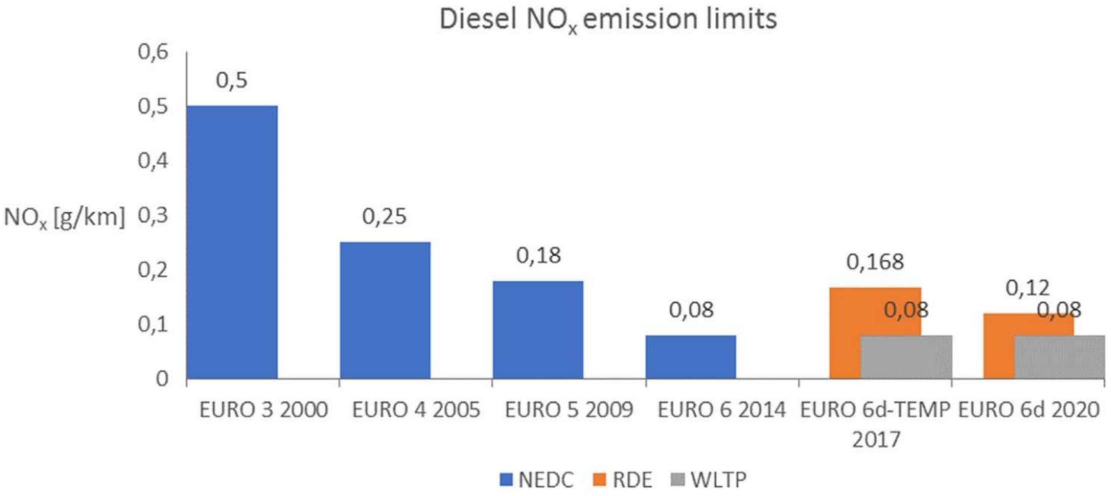


Fig. 15 – Overview of the diesel emission limits for NOx since Euro 3 [6]

4.5.2 Data Evaluation

The emissions produced during the RDE trip are recorded instantaneously and subsequently processed and calculated trough a specific evaluation method. The resulting emission values for the entire RDE trip as well as for the urban part alone must remain below the Not-To-Exceed emissions limits as defined by the following equation [18].

$$NTE_{pollutant} = CF_{pollutant} \cdot Euro6 \tag{6}$$

Until the 4th RDE package came into force on 1st January 2019, two evaluation methods could have been utilized – Moving averaging windows (MAW) or Power binning. Today, only MAW is being used to evaluate the data and is to be shortly summarized.

4.5.3 Moving Averaging Windows (MAW)

The Moving averaging window method consists of sub-dividing the RDE test results in windows based upon a reference CO_2 mass (see Fig. 16 and Fig. 17). The length of each window is defined by 50 % of the CO_2 mass measured during WLTC type-approval test for the specific vehicle. Depending on the sampling frequency, a new window will start with each time increment, unless the vehicle is idling (v < 1 km/h). [6]

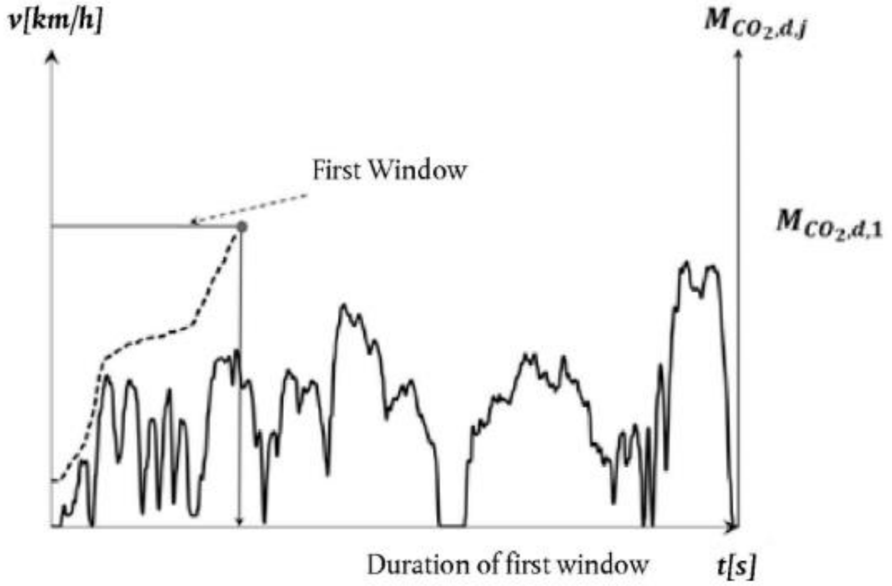


Fig. 16 – Vehicle speed versus time – Vehicle averaged emissions versus time, starting from the first averaging window [19]

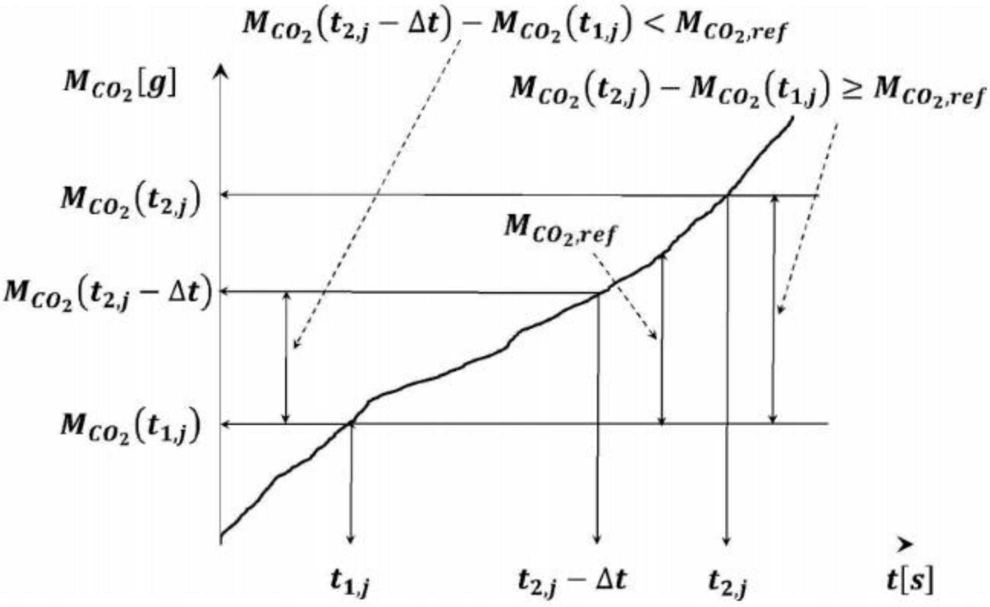


Fig. 17 – Definition of CO_2 mass based averaging windows [19]

Once all windows are completed, a statistical treatment takes place to eliminate the windows that do not represent ‘normal’ driving conditions. In each window, vehicle speeds and CO_2 emissions are averaged, and plotted as a point together with the vehicle CO_2 characteristic curve obtained from the WLTP test (see Table 4 and Fig. 18).

Table 4 – Vehicle CO_2 characteristic curve (adapted from [18])

Vehicle CO_2 characteristic curve			
WLTC phases	Low speed (LS)	High speed (HS)	Extra high speed (EHS)
Reference point	P1	P2	P3
Reference point: Speed [km/h]	18,882	56,664	91,997
Reference point: CO_2 [g/km]	$CO_{2\ LS\text{-}WLTP}$	$CO_{2\ HS\text{-}WLTP}$	$CO_{2\ EHS\text{-}WLTP}$

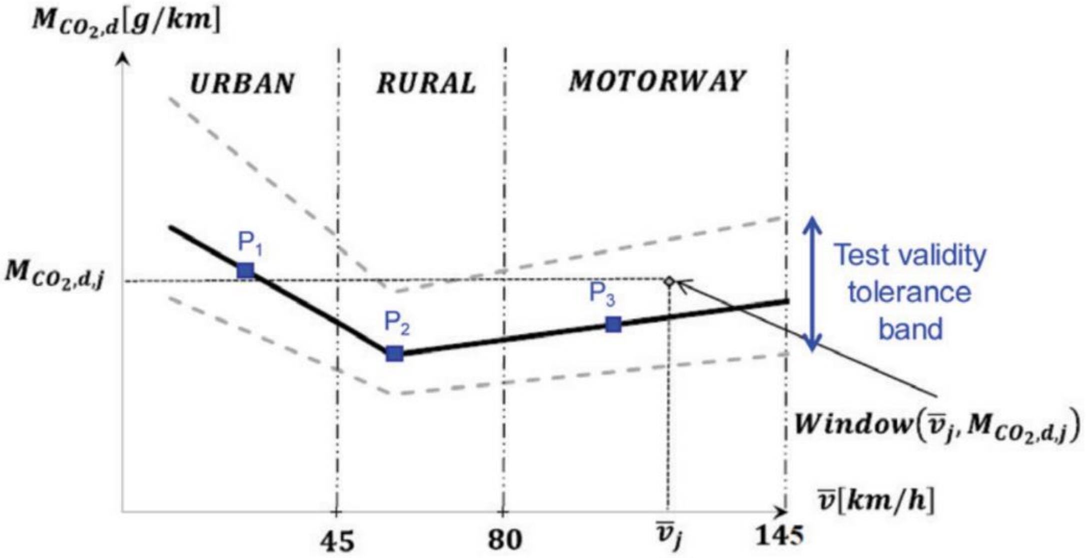


Fig. 18 – Test validation based on vehicle CO_2 characteristic curve [18]

Depending on the driving behavior, the length and time of the windows can differ significantly.

4.5.4 Cold Engine Start

By means of the 3rd RDE package, the focus was put on the inclusion of cold start emissions [6] and the cold start period is now fully included in the urban part of the RDE trip and the whole trip.

Duration of the cold start period is defined the first 5 minutes after engine start or until the coolant temperature (engine temperature) ≥ 70 °C. Other requirements are for example: maximal speed during cold start ≤ 60 km/h, the average speed (including stops) shall be between 15 and 40 km/h, total stop time during cold start < 90 s and idling after ignition < 15 s. [18]

5 Summary of the Research Part

The population of GDI vehicles has been increasing, driven by CO_2 and/or fuel economy requirements. Emissions from the growing GDI vehicle fleet are a public health concern and a potential major source of ambient particle pollution in highly populated urban areas. [17]

At least for diesel NOx, the European emission limits have failed due to an unrealistic driving cycle and a lenient framework that allows interpretation. Real driving emissions (RDE) testing by means of portable emissions measurement systems (PEMS) has the potential to change this situation drastically and to force car manufacturers to ensure compliance with the emission regulation over the engine operation range. [6]

Despite watered-down conformity factors, EU car manufacturers are the first worldwide to impose RDE testing of passenger cars by means of PEMS during type-approval. [6]

6 Calibration & Emissions Analysis

All the tests mentioned in the parts above are designed to give us total amount of emissions out of which the emissions per kilometer are then calculated. However, for engineering purposes of designing a new vehicle or for purposes of calibration, it is necessary to analyze the instantaneous emission values (usually at sample rate of 1 Hz) depending on the parameters set and measured on the engine and its aftertreatment. In this way it is possible to identify risky operating modes and detect potential problems not only in terms of emissions.

Calibration is a process of looking for the best possible setting of the system in order to meet specified targets. The system in this case is a vehicle with its ECU (Engine Control Unit). The best possible setting is based on the strategies (ECU software) and there is the need to calibrate the controllable parameters to achieve the desired targets.

6.1 Emissions Analysis

As described in the research part of this thesis, it has always been a challenge to test passenger cars in a cycle that would cover all the possible operating conditions in which cars are utilized in real world. In contrast to a HD (Heavy Duty) vehicle which is usually used in predictable ways and can be therefore designed and tested accordingly, LD (Light Duty) vehicle can be used in many ways that can differ significantly and the vehicle should always comply with the regulations. In Fig. 19 is shown how the test cycles evolved throughout time and following trends can be observed:

- Duration of the test is increasing – 20 min. for NEDC, 30 min. for WLTC and 90 to 120 min. for RDE (This trend has been subject of criticism and the impact of cold start will be further discussed)
- Distance of the test is increasing – 11 km for NEDC, 23.3 km for WLTC and usually around 90 km for RDE
- Later tests have more dynamic driving profile, resulting in higher engine loads, and better match the real driving
- Average speeds are getting higher (It is worth noting that RDE test must comply with the regulations not just as a total, but its urban part undergoes specific regulations separately as well)

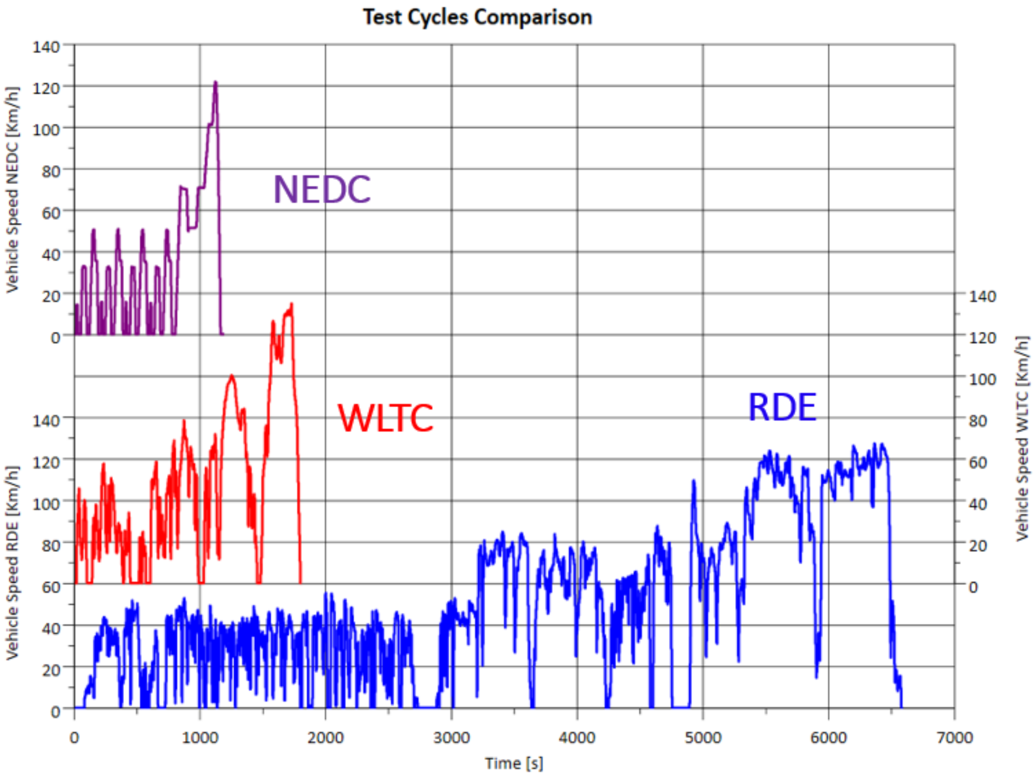


Fig. 19 – Test cycles vehicle speed profiles comparison

6.2 Ricardo RDE Data Mining Tool Description

This MATLAB based tool was created by engineers in Ricardo to provide customers with another angle of view regarding their emissions tests. This tool enables an engineer to merge data from a big number of tests and analyze it all at once. This statistical approach allows him to see all the reoccurring events better and to identify the risky areas and operating conditions.

This tool is not meant to show proportions of tests above legal limit. It highlights risk areas for different types of emissions that need to be analyzed closer. To smoothen the emission curve, moving average windows of adjustable length are applied (default setting is averaging over 5 values – 5 seconds at 1 Hz sampling rate). The limit line that classifies the area as risky (see Fig. 20) is usually set to a legal limit value (note that conformity factors are not applied here).

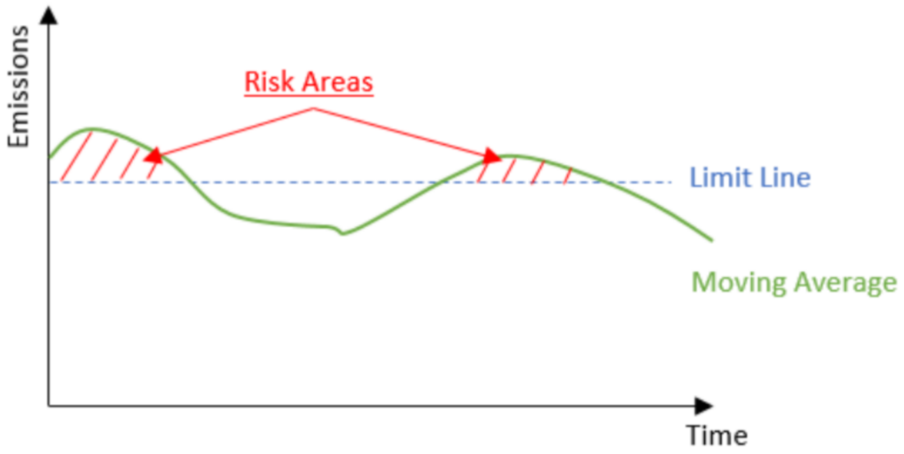
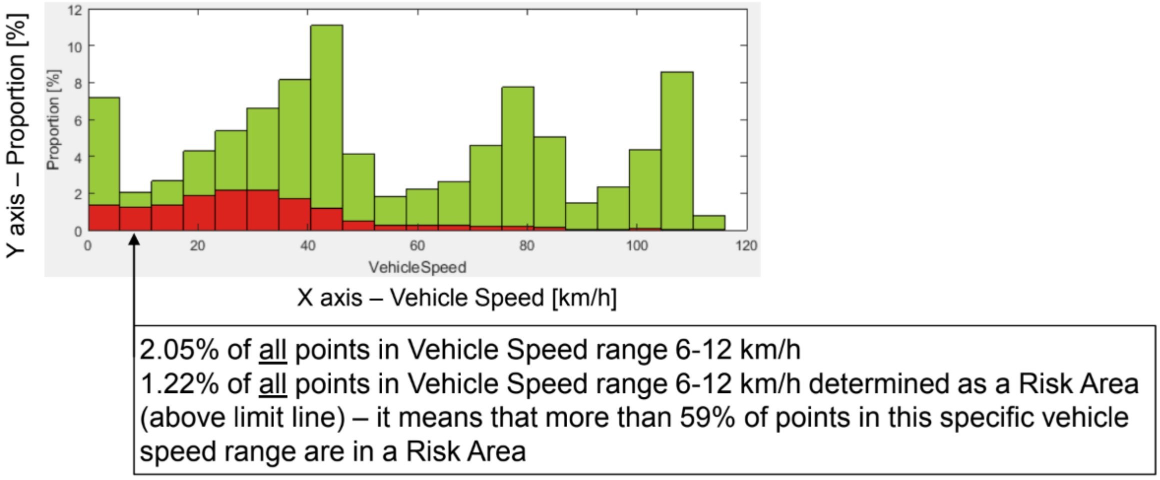


Fig. 20 – Ricardo RDE Data Mining Tool principle [20]

6.2.1 RDE Data Mining Tool Output

It is important to read the charts created by the tool correctly. Different X axis are available (Vehicle Speed, Engine Speed, Catalyst Temperature, etc. – they are defined by user in data preparation process). Y axis represents a proportion of points in a certain X axis range (see Fig. 21). Each green colored column is a proportion of all points in a certain X axis range (sum of all green columns is 100 % for unfiltered data). Each red column indicates a proportion of risk points in a certain X axis range.



2.05% of all points in Vehicle Speed range 6-12 km/h
1.22% of all points in Vehicle Speed range 6-12 km/h determined as a Risk Area (above limit line) – it means that more than 59% of points in this specific vehicle speed range are in a Risk Area

Fig. 21 – RDE Data Mining Tool output interpretation example [20]

Additionally, results that meet certain criteria (are above or below certain threshold) can be filtered. This feature can be very useful when analyzing e.g. cold start.

6.3 Virtual Calibration

The efforts to improve the performances and reduce pollutant emissions of passenger car powertrains have led to technological evolutions on both engine and exhaust aftertreatment sides. The multitude of different technologies has increased the system complexity. Stable control and robust monitoring of the Engine Control Unit (ECU) become mandatory. However, this tends to exponentially increase calibration effort. In addition, the number of vehicle and powertrain derivatives is significantly scaled-up. Therefore, an efficient and cost-optimized ECU calibration is essential in calibration projects for achieving high quality targets and managing enlarged testing matrix to ensure seamless validation. Frontloading through virtualization enables a substantial reduction of required test loops on prototype vehicles. [22]

The trend of virtual calibration is very reasonable in terms of productivity efficiency, development time shortening and cost reduction. Model- or big data- or cloud-based methods mean a revolution not just in automotive industry and are becoming an indispensable component of the development. Theoretically, the majority of tests especially during calibration of derivatives could be spared with proper utilization of available data. The virtual calibration is of great relevance for OEMs, because of the challenging and time consuming RDE testing. These facts are motivation for this thesis as it describes one of many ways of data analysis.

7 Aims and Objectives

The focus of the practical part of this thesis is to identify modes of operations and combinations of conditions that substantially contribute to the total emissions (short very high emission episodes as well as longer periods of moderately high emissions) and the potential for emissions reduction is to be explored.

Identification of possible calibration changes using RDE Data Mining Tool could serve as sort of a bridge between classical calibration and the virtual calibration. Data acquired via real-world testing as well as model-based simulations can be analyzed through the tool and in the following parts, this calibration statistical approach is to be demonstrated

The thesis is written in close cooperation with Ricardo Prague Technical Centre which provided the necessary anonymized data for the analysis. In order to get a basic idea of the vehicle type and what behavior is to be expected, the data were acquired on a hatchback fitted with three-cylinder 1.2 l turbocharged GDI engine equipped with close coupled TWC and GPF as an aftertreatment. The data have been collected under different conditions and all the tests were conducted recently in the range of a half of a year.

As the parameters suggest, the pre-assumption is that the engine complies with the Euro 6d limits

8 Ricardo RDE Data Mining Tool Analysis

8.1.1 RDE and WLTC Comparison

First, I would like to use the Ricardo RDE Data Mining Tool to describe the main differences between WLTP cycle (WLTC) and RDE test procedure and why it is so important, that RDE have become a part of the emissions testing procedure. For this purpose, I have analyzed over 19 hours of WLTC testing data in comparison with over 17 hours of RDE testing data.

All acquired points are plotted in Fig. 22, engine speed as X axis and relative air load[1] as the Y axis. This chart clearly shows the distribution of engine load during WLTC compared to the distribution during RDE.

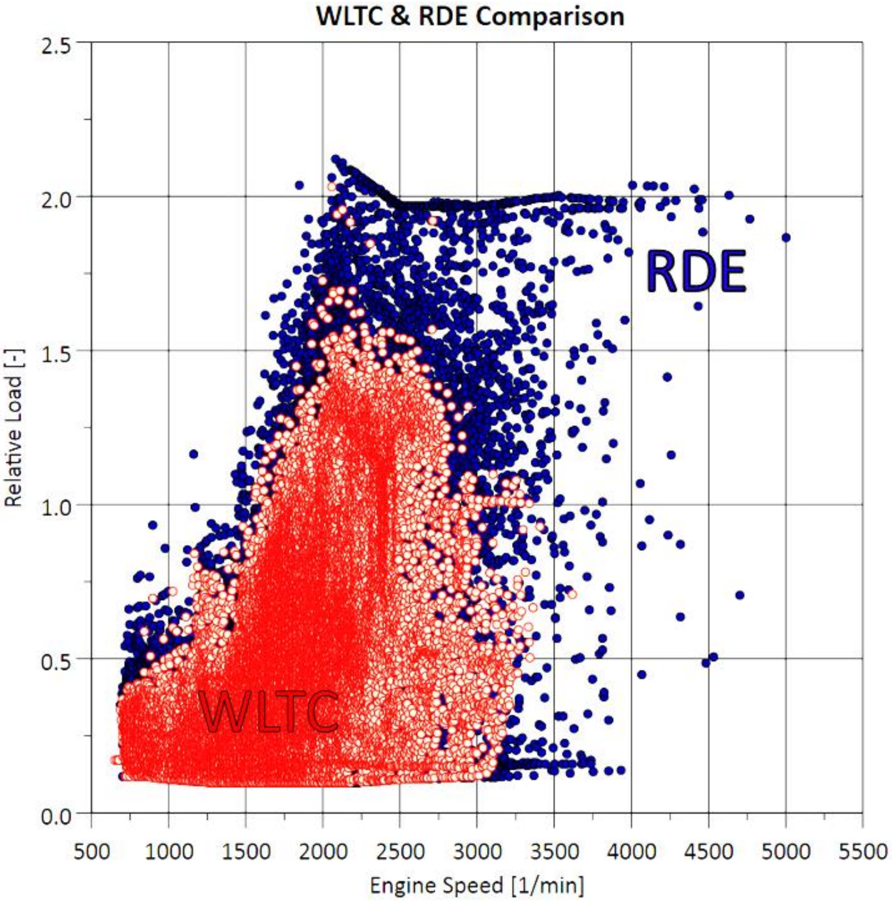


Fig. 22 – WLTC & RDE Comparison

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[1] "Load" means how much power is required from the engine for the car to have some speed and acceleration. When a vehicle is cruising on the highway, it only needs a small percentage of its total available power output to maintain speed. We calculate the load based upon the following formula [23]:

$$Engine\_Load = \frac{Current\_Airflow}{Max\_Airflow(Rpm) \cdot \frac{Baro}{29.92} \cdot \sqrt{\frac{298}{T_{amb}+273}}} . [23]$$

RDE test demands greater power output in lower rpm and it reaches much further on the engine map in direction of higher loads and more aggressive driving. In WLTC, only few points are beyond 3 250 rpm, whereas in RDE, the engine speed could be as high as 4 500 rpm.

The dark blue points representing the RDE tests are distributed more evenly throughout a larger part of possible engine load conditions which corresponds with the main purpose of introduction of this testing procedure - to capture the real traffic better.

Before looking at RDE Tool outputs, it is worth noting that only total emissions in g/km and urban total emissions in g/km are so far regulated which means that cumulated emitted mass is simply divided by the cumulated distance. While looking at the data via RDE Tool, instantaneous emissions averaged only over five consecutive values (to smoothen the data) are analyzed. This approach is of greater relevance for developing purposes and offers better insight that is needed in order to explore risky periods, that contribute the most to higher emissions.

The limit for NOx was set to 0,06 g/km (Euro 6d), for PN to $6 \cdot 10^{11}$ #/km (Euro 6d) and no conformity factors were applied, given that current PEMS are in line with the stationary laboratory equipment that is used nowadays, in terms of reliability and accuracy [6].

Ricardo RDE Data Mining Tool NOx analysis can be seen in Fig. 23. Vehicle speed, engine speed and engine temperature channels were chosen in order to draw the first conclusions.

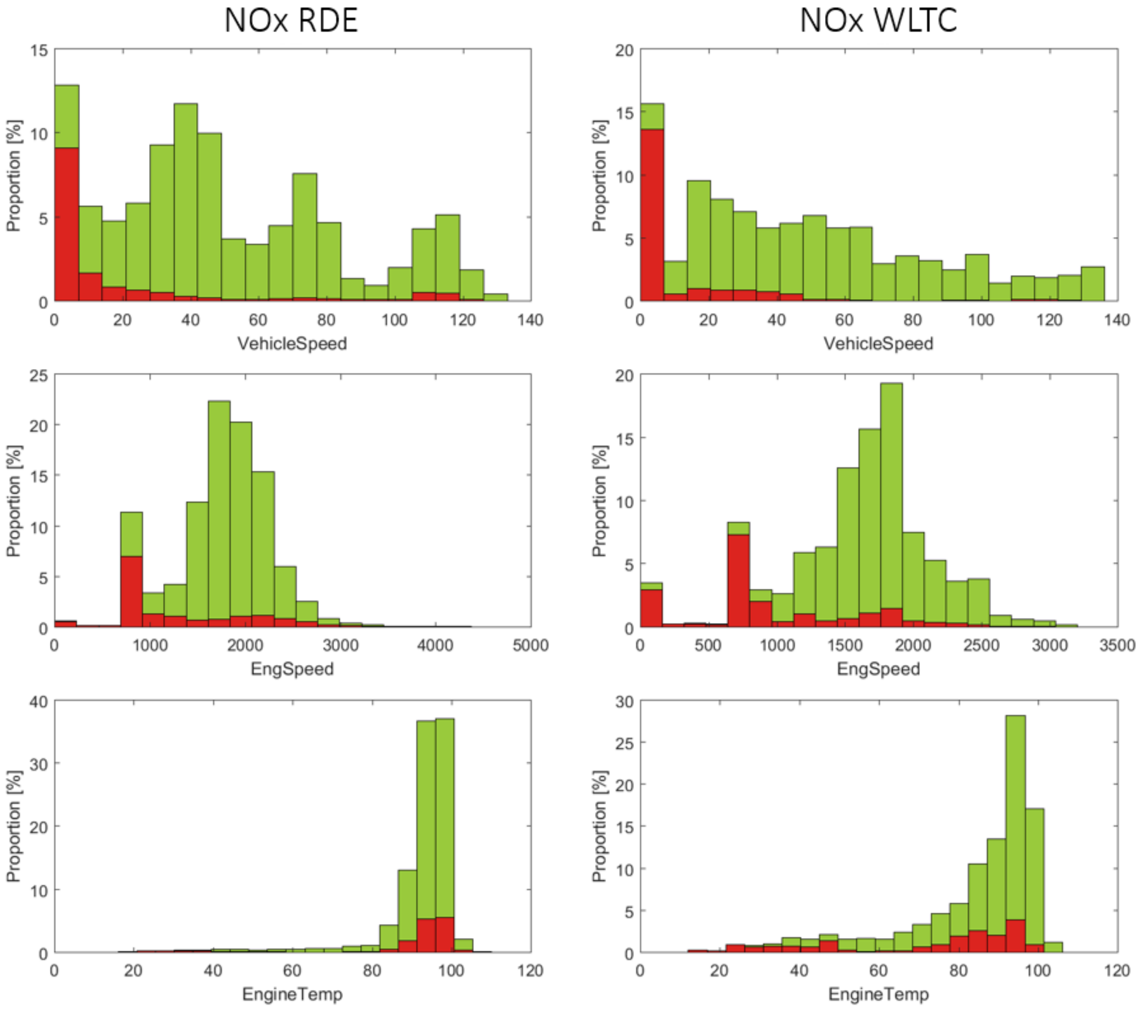

Fig. 23 – NOx WLTC and RDE comparison – vehicle speed [km/h], engine speed [rpm] and engine temperature [°C]

There are clear differences in vehicle speed distribution at the first sight (green columns). RDE has its peaks around the usual real-world speeds (50 km/h in a town, 70 to 80 km/h outside of a town and around 120 km/h on a highway). About 12 % of the RDE tests were driven in speeds around 40 km/h (urban phase). WLTC is distributed more evenly over the whole range of speeds.

The riskiest part of both tests is when vehicle is not moving. WLTC has bigger portion of "not moving" points (more than 15 %) as well as more interventions of the Start & Stop system (engine speed is zero). However, as the regulated unit is g/km, are all the points in which vehicle speed is below 1 km/h are officially excluded[2]. As an example, the same filter is applied to the NOx RDE test data in Fig. 24.

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[2] Stopped vehicle with its engine on would have theoretically infinite emissions in grams per driven km.

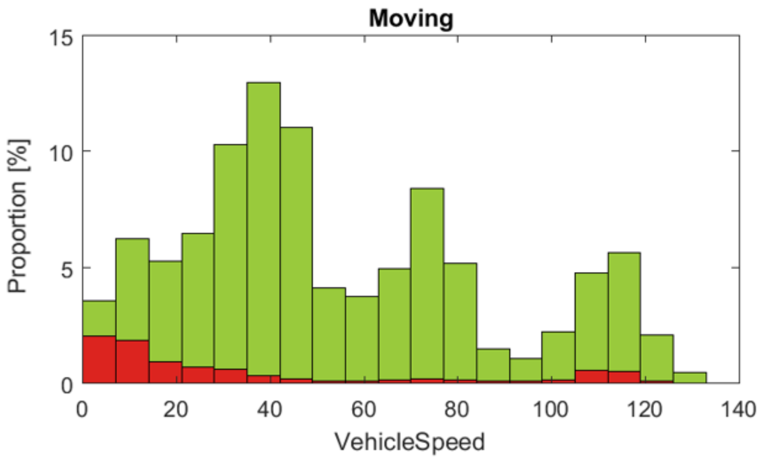


Fig. 24 – NOx RDE – vehicle speed [km/h] > 1 km/h

Lower speeds have generally higher emissions due to several reasons. Vehicle speed is usually not constant (with exception of traffic jams) and a lot of accelerations take place. In RDE, about 25 % in vehicle speed range 10-20 km/h are above the limit (Fig. 24).

In RDE, there is a bigger portion of risky areas in lower speeds compared to WLTC which could be attributed to the speeds during a beginning of the tests (could be seen in Fig. 19). In WLTC, vehicle accelerates within the first minute, whereas in RDE, the vehicle needs to pull out of the parking slot for example or get to main road before actual driving.

The next risky period is driving at highway. In RDE, the portion of highway periods is higher (see Fig. 19) compared to WLTC. In these periods, there is higher demand for engine power output, which generally leads to higher emissions. In RDE, around 10 % of points in vehicle speed range from 110 to 120 km/h is risky. In WLTC, around 6 % of points in the same vehicle speed range are risky.

As already demonstrated in Fig. 22, in RDE, engine speed reaches higher rpm than in WLTC. After closer analysis of Fig. 23, around 40 % of points in ranges above 3 750 rpm are in risky area. WLTC has a limited range of engine speed and it is not possible to draw any conclusions about higher rpm.

The most noticeable difference between RDE and WLTC is in the distribution of engine temperature. As WLTC test time is approximately three times shorter than the RDE test time, the effects of cold start and engine warmup have greater impact on the overall results. Most of the NOx emissions are emitted during the cold start, as the catalyst needs some time to warm up in order to fulfill its purpose properly. In engine temperature ranges around 50 °C, 40 % of points are in the risky area for both RDE and WLTC. Continuing further in direction of lower temperatures, the percentage increases steadily up to almost 100 % at the very start of the engine.

Based on previous observations, a conclusion can be made that the worst periods of higher emissions are aggressive accelerations and cold start. Cold start as well as aggressive driving can be filtered and viewed separately using RDE Tool. Cold start is defined as all points in which engine temperature is below 70 °C (referred to as "Not Warm Engine") and aggressive driving definition can be derived from Fig. 25 (according to EU 2018/1832 RDE regulation).

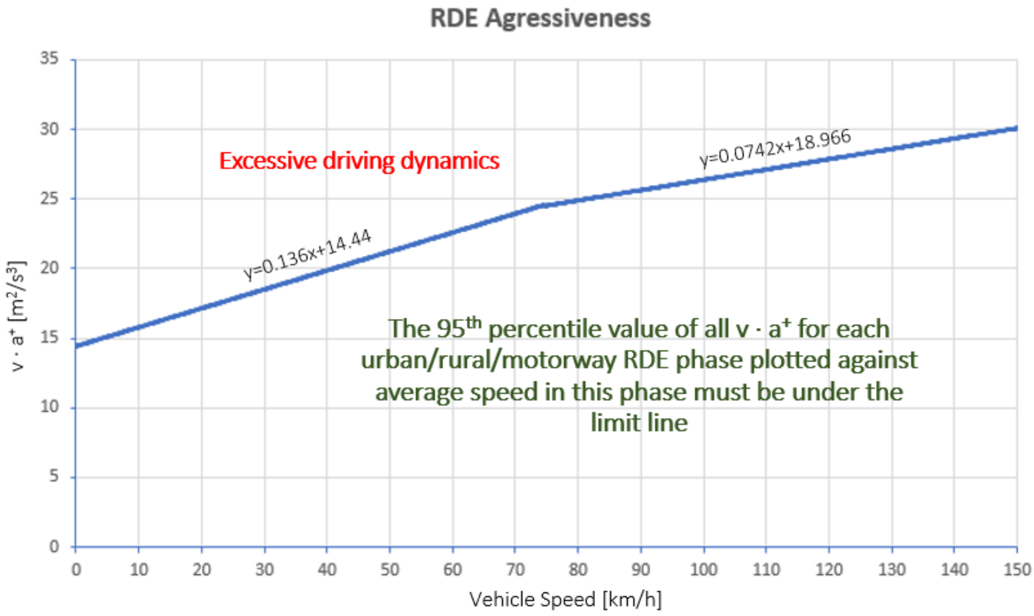


Fig. 25 – Definition of driving dynamics upper limit

8.1.2 WLTC Data Analysis Problem

The main advantage of RDE Tool is the ability to analyze more tests at once and to eliminate any random peak occurrences in the data. Based on Fig. 26, the assumption could be made, that there is a problem in range of engine temperatures between 40 and 50 °C.

Note that the Y-axis always represents the proportion of the certain range of values among all the values fulfilling certain criteria. For example, in Fig. 26, around 8 % of all "Not Warm Engine" engine temperature values were in range 44-46 km/h and around 5 % in the same range were risky. This means that more than 50 % of points were risky in this specific range out of the specifically filtered data for cold start.

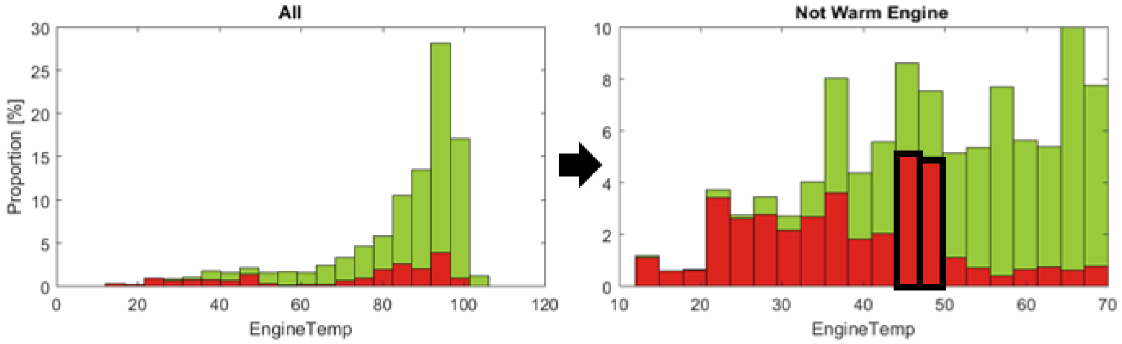


Fig. 26 – WLTC NOx – cold start exclusion (engine temperature [°C])

However, this would be an incorrect conclusion in this case. In Fig. 27, 10 WLTC tests are time-synchronized. The vehicle speed is always the same (test repeatability). The green curve is the most representative temperature, which differs throughout the tests, as the starting temperature changes and there are slight changes in its behavior since there have probably been some changes to calibration between development tests.

The NOx emissions curves are very similar for all the tests. This fact results in eliminating the advantage of RDE Tool approach to data analysis and could lead to misinterpretation of the RDE Tool output in similar way that was demonstrated. For this reason, RDE data only will be analyzed in further parts.

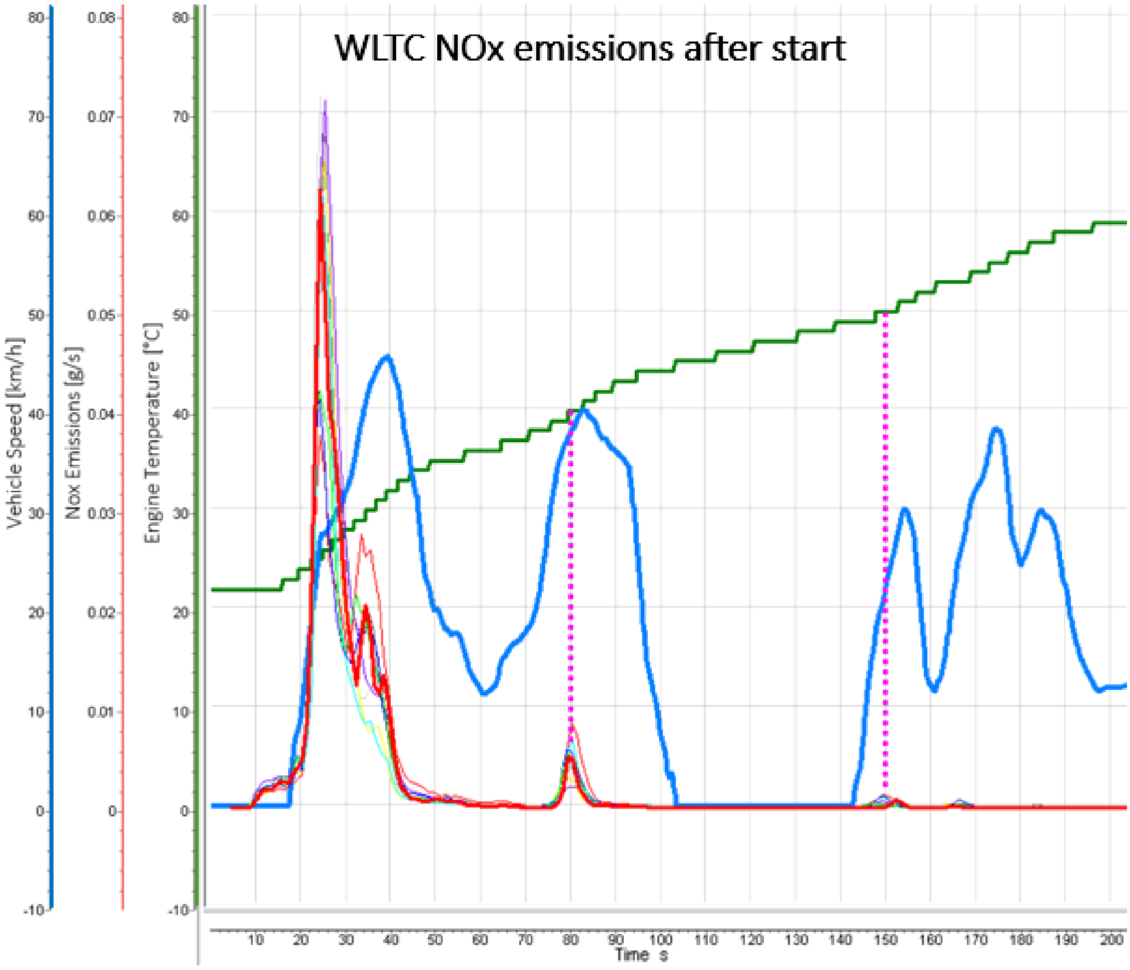


Fig. 27 – NOx emissions of 10 different WLTC tests after start

8.1.3 RDE Data Analysis

With RDE data, RDE Tool can work effectively and show all its strengths. Based on conclusions made in previous parts, data from cold start (engine temperature < 70 °C) and aggressive driving ($v \cdot a^+$ above limit) were filtered (as shown in Fig. 28 for cold engine as an example).

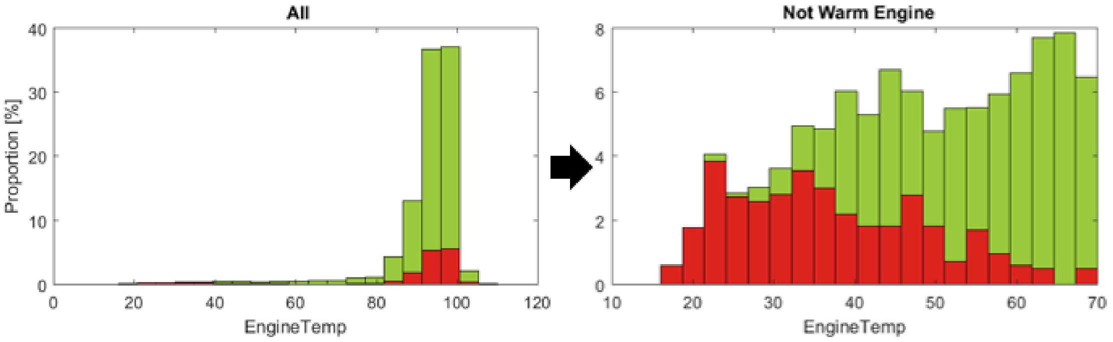


Fig. 28 – RDE NOx – cold start exclusion (engine temperature [°C])

The resulting charts for NOx as well as for PN emissions depending on vehicle speed, engine speed, relative air load and engine temperature are in Appendix 1.

NOx emissions, considered to be the most problematic, were above the limit line in over 30,5 % points for aggressive driving and 36 % for cold start. From all the points in which vehicle speed was greater than 1 km/h, only 9 % were above the limit line. These numbers show that high NOx emissions risk areas exist, but the overall proportion of risk is relatively low.

PN emissions results turned out to be much riskier in terms on the legal limit even with the GPF installed as part of the aftertreatment system. More than 45 % of points were above the limit line for aggressive driving and over 52 % for cold start. From all the points in which vehicle speed was greater than 1 km/h, 14 % were above the limit line.

These percentages show that there is a greater risk for high emissions during cold start than there is during aggressive driving periods. This claim is further confirmed when looking at the proportion of points filtered as cold start and as aggressive driving relative to all test points. For this set of tests 4,25 % of the points were filtered as cold start and just 1,53 % as aggressive driving.

At this point it is important to underline the fact, that these percentages do not represent the extent to which the tests were above the legal limit. They are just pointing at the risk areas and the severity of exceeding the limit is to be further investigated. Finally, this analysis is very different from the data evaluation method (MAW) used in homologation process. The tests were not checked for their validity based on RDE requirements and raw data were used without applying any “filters” or conformity factors.

Cold start was highlighted as the most relevant risk area and it is a subject of more detailed analysis in the next part of the thesis.

9 Cold Start Analysis

"A major accomplishment in the framework of RDE testing is the inclusion of the cold start in the post-processing of raw PEMS data. Originally the first five minutes of registration were excluded from the data, however cold starts contribute significantly to the overall vehicle emissions. By including cold start emission monitoring in the RDE testing, OEMs are enforced to make sure catalysts warm up quickly to get cold start emissions under control as soon as possible." [6]

In Fig. 29, a few of the most important RDE channels describing the cold start are plotted. In about 6 seconds into the test, the engine is started (see the purple engine speed). At this moment, the engine mode (blue line) is set to TWC heating to warm up the catalyst as quickly as possible in order for it to fulfill its function properly (more about engine modes in the next part of the thesis). The engine coolant temperature (red line) starts to rise slowly, and it is of great interest that it reaches the threshold of 70 °C as soon as possible (the transition from cold start to optimal warm calibration). This threshold is in this case reached after around 4 minutes and 15 seconds from engine start.

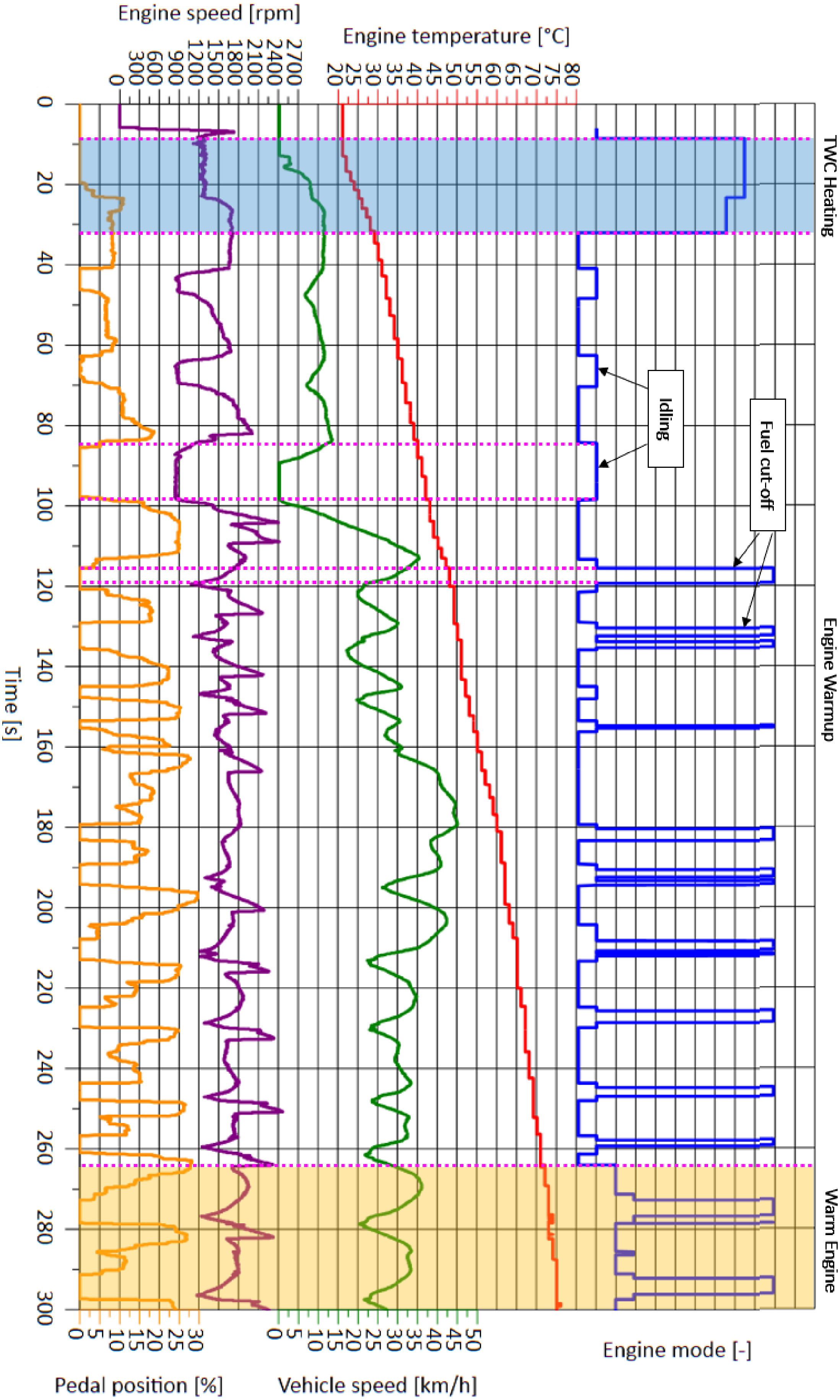


Fig. 29 – Cold start

In the TWC heating part, the goal is to heat the TWC up to at least 300 °C as soon as possible which takes around one minute in this case. When it comes to acceleration during this phase, it is unavoidable that NOx peak occurs as the catalytic conversion cannot take place. In order to raise the catalyst temperature quickly, rich mixture is injected and in connection with the cold engine, PN peak occurs as well (see Fig. 30).

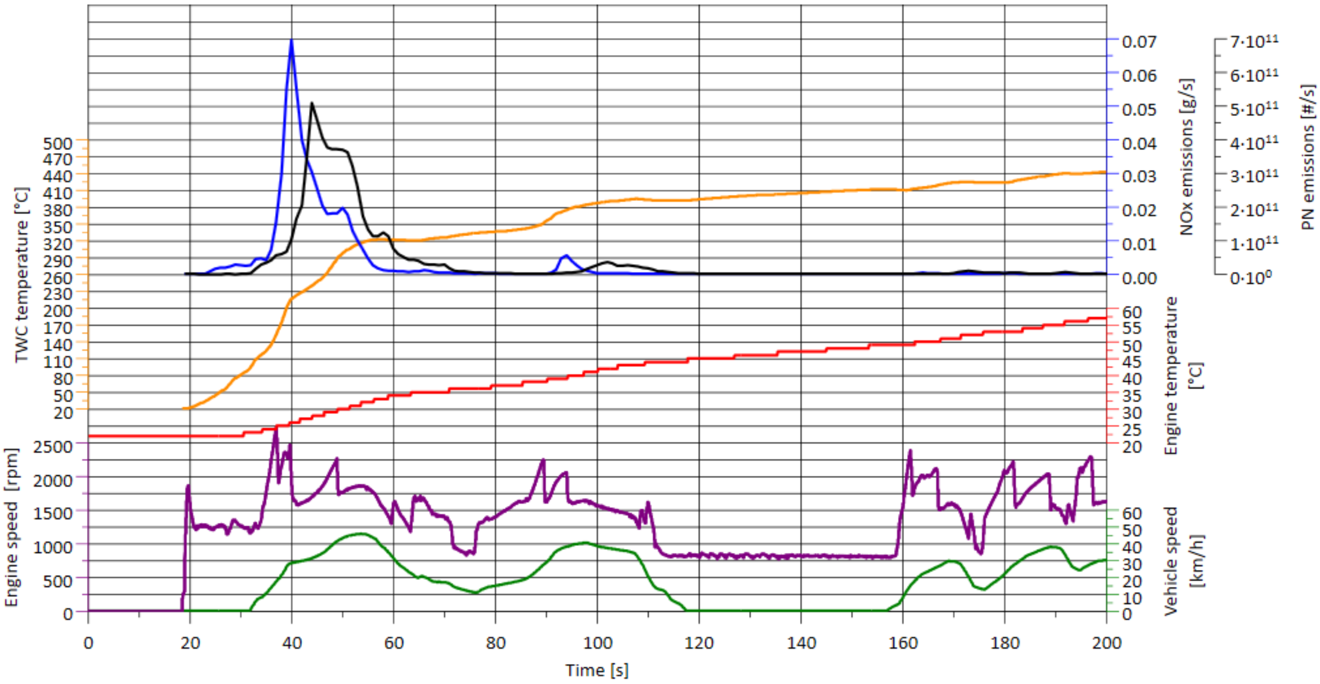


Fig. 30 – Acceleration at the beginning of WLTC

The importance of the cold start problematics is very nicely documented by the results (see Fig. 31) of the De Gennaro et al. data acquisition campaign from May 2011 in Italy [24], which involved over 50 000 conventional fuel vehicles equipped with data-logging devices.

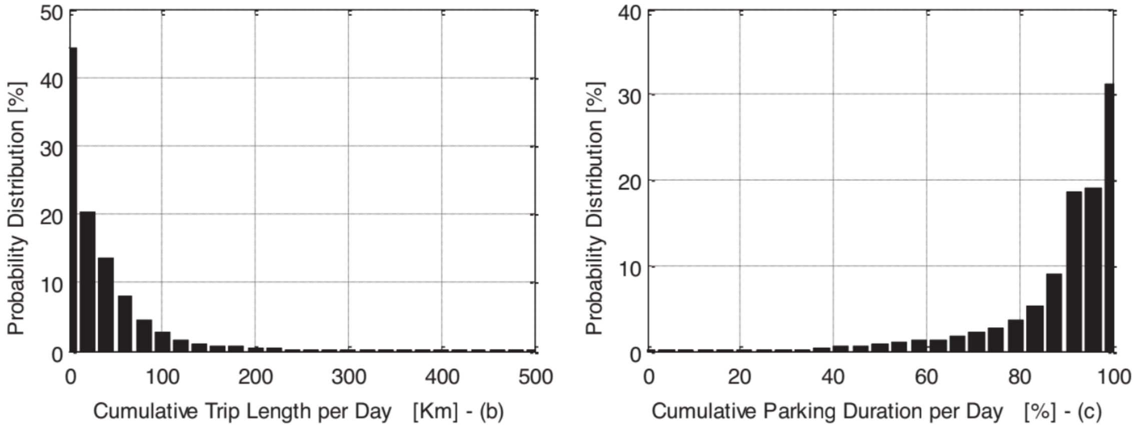


Fig. 31 – Probability distribution histograms of cumulative trip length and cumulative parking duration per day [24]

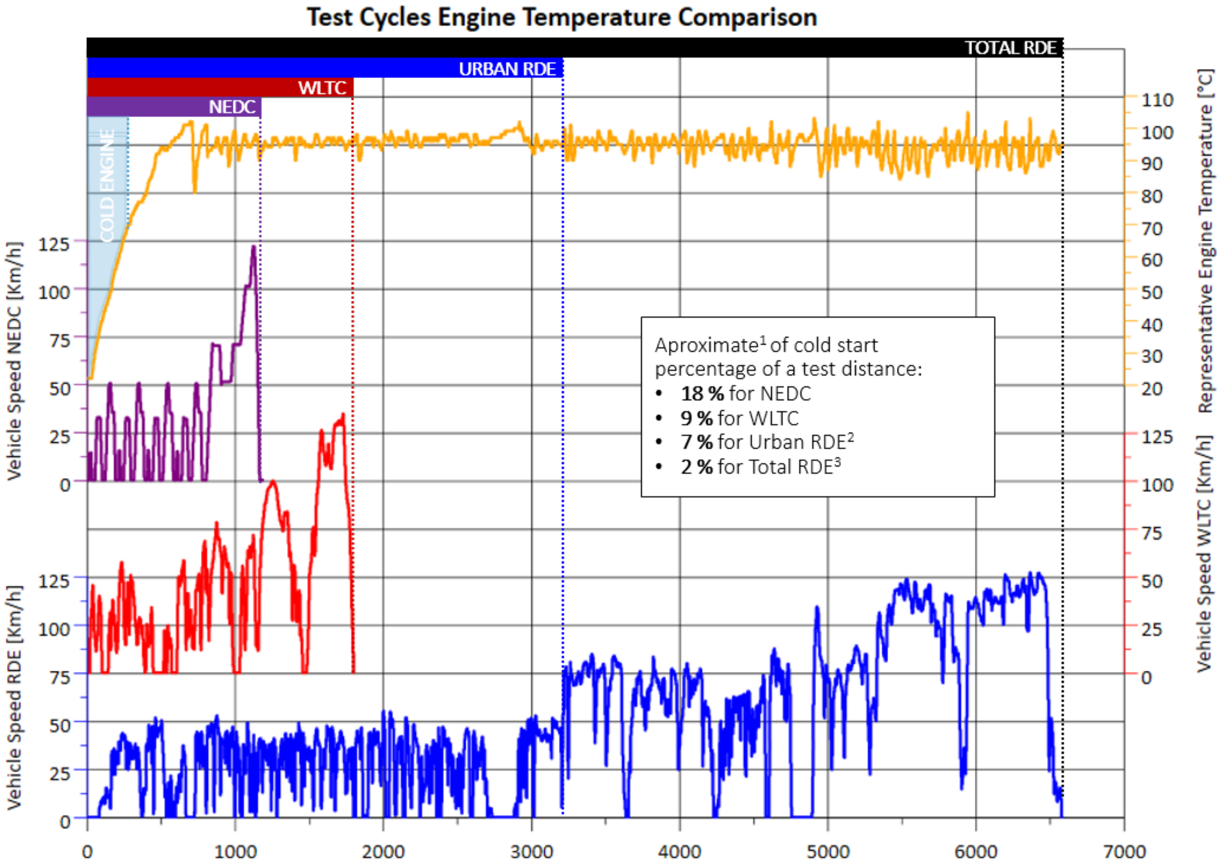
"More than 90 % of vehicles are parked at any given hour of the averaged day, being never less than 85 % considering each day in the month. The average number of trips per day, per vehicle, is approximately six, with an averaged trip length which lies between 5 km (day) and 20 km (night). The average trip speed lies between 20 km/h (day) and 40 km/h (night) The cumulative distribution calculated per trip, per day and per week, show that 90 % of the trips are below 20 km." [24]

The study was meant to demonstrate the reasonability of electric vehicle usage in towns. The most important fact arising from this campaign is how short the average trip is, how low the average speeds are, and that majority of these trips are cold due to long parking intervals between consecutive trips.

9.1 Impact of Cold Start on Urban RDE

Cold start has been a great concern of OEMs for many years as the emissions resulting from cold engine and aftertreatment system are hardly avoidable. However, the applicable regulation changed a lot throughout time, and it has always been subject of strong automotive industry lobby.

As the regulated emissions are measured in g/km, resp. in #/km, the cold start contribution diminished with increasing test distance. Due to the longer cycle length, cold start contribution in case of the WLTC is approximately half of the contribution in case of the NEDC. To put it simply, the peak of emitted pollutants at the beginning of the test gets distributed into more kilometers which causes the resulting emission value in g/km, resp. in #/km to decrease. The different cycles and how the cold start affect them differently is shown in Fig. 32. Percentages based on test distance are more relevant due to the regulated emissions units.



Aproximate[1] of cold start percentage of a test distance:

- **18 %** for NEDC
- **9 %** for WLTC
- **7 %** for Urban RDE[2]
- **2 %** for Total RDE[3]

[1] cold start aproximatelly 2 km long
[2] Urban RDE aproximatelly 30 km long
[3] Total RDE aproximatelly 90 km long

Fig. 32 – Impact of cold start on different test cycles

Since the urban part of the RDE test must comply with the same limits the whole (total) RDE test, the relevance of cold start contribution to urban phase is greater. To further examine this fact, urban parts from four different RDE tests were extracted and from those, only the periods in which engine temperature was below 70 °C were excluded. Subsequently, raw data from each complete urban part were compared with data from this urban part with excluded cold start. The goal was to investigate the cold start contribution percentage to urban part NOx as well as PN emissions (see Fig. 33).

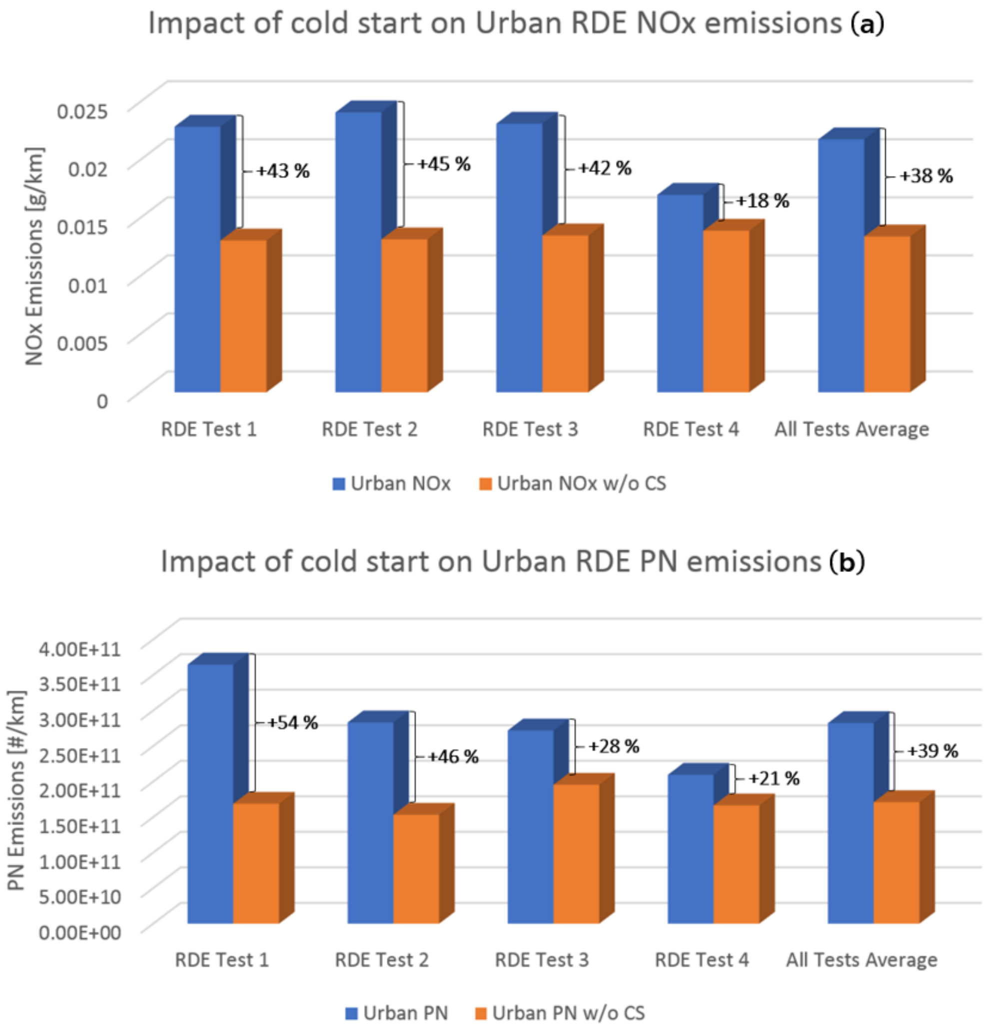


Fig. 33 – Impact of cold start on Urban RDE NOx (a) and PN (b) emissions

On average, the cold start makes up to 40 % of urban RDE NOx and PN emissions. Impact of cold start emissions on urban RDE can differ significantly depending on the very beginning the test (driving aggressivity etc.). This demonstrates the importance of the inclusion of the cold start period into the RDE testing procedure in order to evaluate the overall vehicle emissions properly.

9.2 Urban Phase Length Study

Fig. 34 shows how would shortening of the urban phase affect the urban RDE emissions if raw data were evaluated (which is not the case in reality!). Cumulative emissions are plotted over distance. At the beginning, the values are very high due to the cold start peak, low vehicle speeds and therefore lower rate of distance accumulation. As the engine warms up and vehicle accumulates distance, emissions in g/km, resp. in #/km sink.

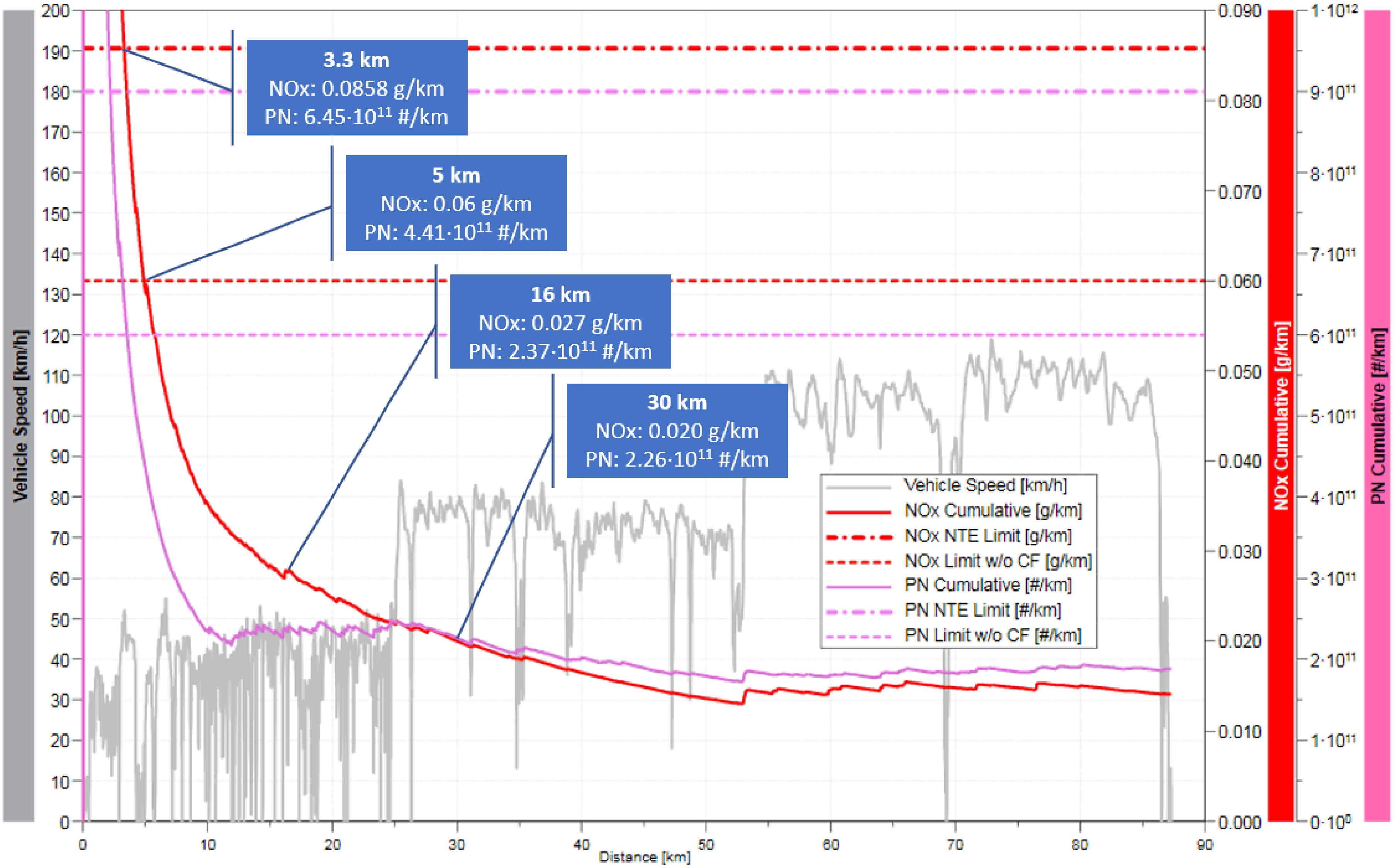


Fig. 34 – Urban phase length study

For the test example in Fig. 34 (note that RDE tests can differ significantly as demonstrated above), following conclusions can be made. The shortest possible urban phase defined in RDE legislation is 16 km. If driven at this minimum, NOx emissions would be about 35 % higher than if usual distance of around 30 km was driven (5 % higher for PN emissions). If shortened down to 5 km, the test would no longer comply with EURO 6d NOx limit without CF. Until reaching the distance of approximately 3,3 km, the vehicle did not comply even with the NTE limit for NOx emissions.

At this point, EURO 7 legislation is being prepared to come into force as early as in 2025 (probably around 2027). Some OEMs might put lawmakers under pressure of shortening the RDE procedure. The question is if it would mean an advantage in approval process or rather disadvantage.

10 Absolute Emissions Analysis

In RDE Data Mining Tool part, risk areas were identified only considering the proportions of the tests over the limit. Cold start was identified as the riskiest part and accordingly examined in the part above. However, in order to be able to assess an overall high emissions risks during the RDE testing, it is necessary to analyze the whole test in absolute emissions values.

In Fig. 35, CO_2, NOx and PN instantaneous emissions are plotted together with cumulated grams, resp. particles over the whole test and the vehicle speed. At the beginning, the cold start peaks in NOx and PN can be clearly observed, the emissions are than cumulated steadily throughout the urban and rural part. An increase in NOx and PN emissions can be seen during the highway phase, where there is a greater demand for power and peaks especially during accelerations at higher speeds are hardly avoidable (more in following parts).

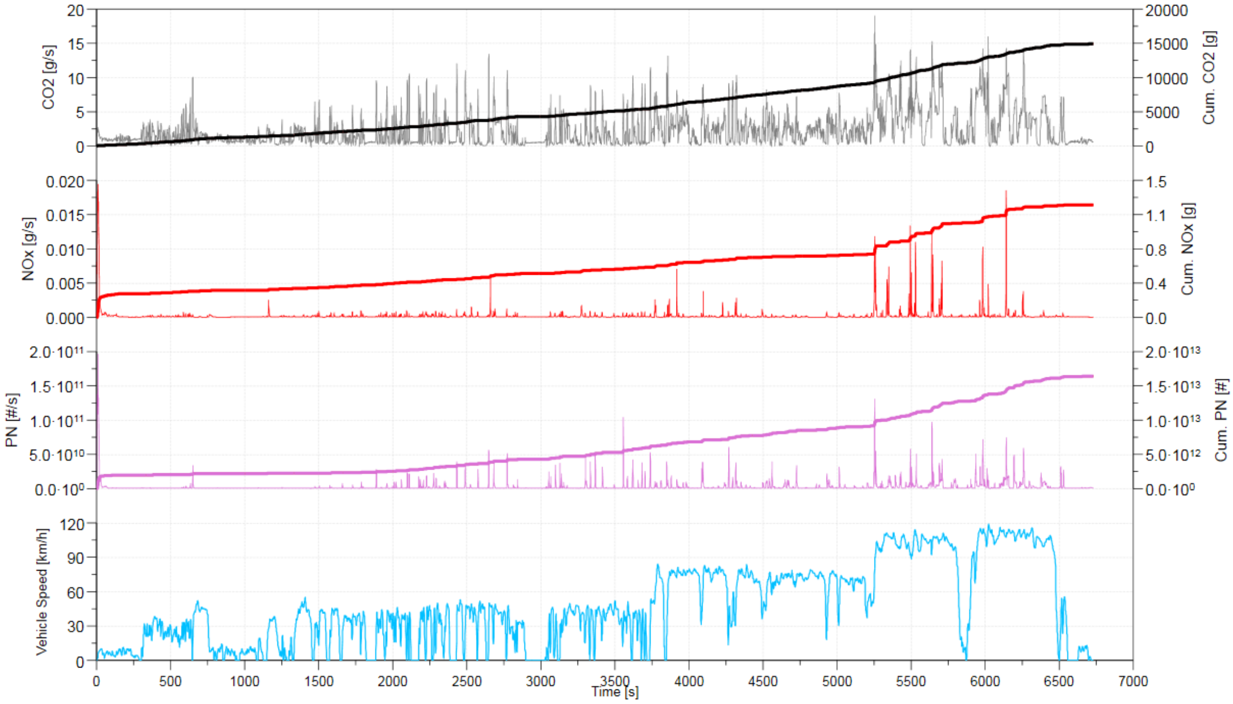


Fig. 35 – CO_2, NOx and PN instantaneous and cumulated emissions

It is very important to consider the way in which RDE data are evaluated. By the latest regulation, Moving Averaging Window (MAW) evaluation method is used as described in the research part of this thesis. To demonstrate how the cold start emission peak and highway driving is projected into the MAWs, I have plotted EMROAD processed data (cumulative MAW emissions) of three different RDE tests (see Fig. 36). My intention at this point was to examine how the curve of MAWs in RDE tests looks like since the tests can differ significantly.

Fig. 36 gives an overview of how the absolute emissions are distributed throughout the test (vehicle speed illustrates the phases of the test).

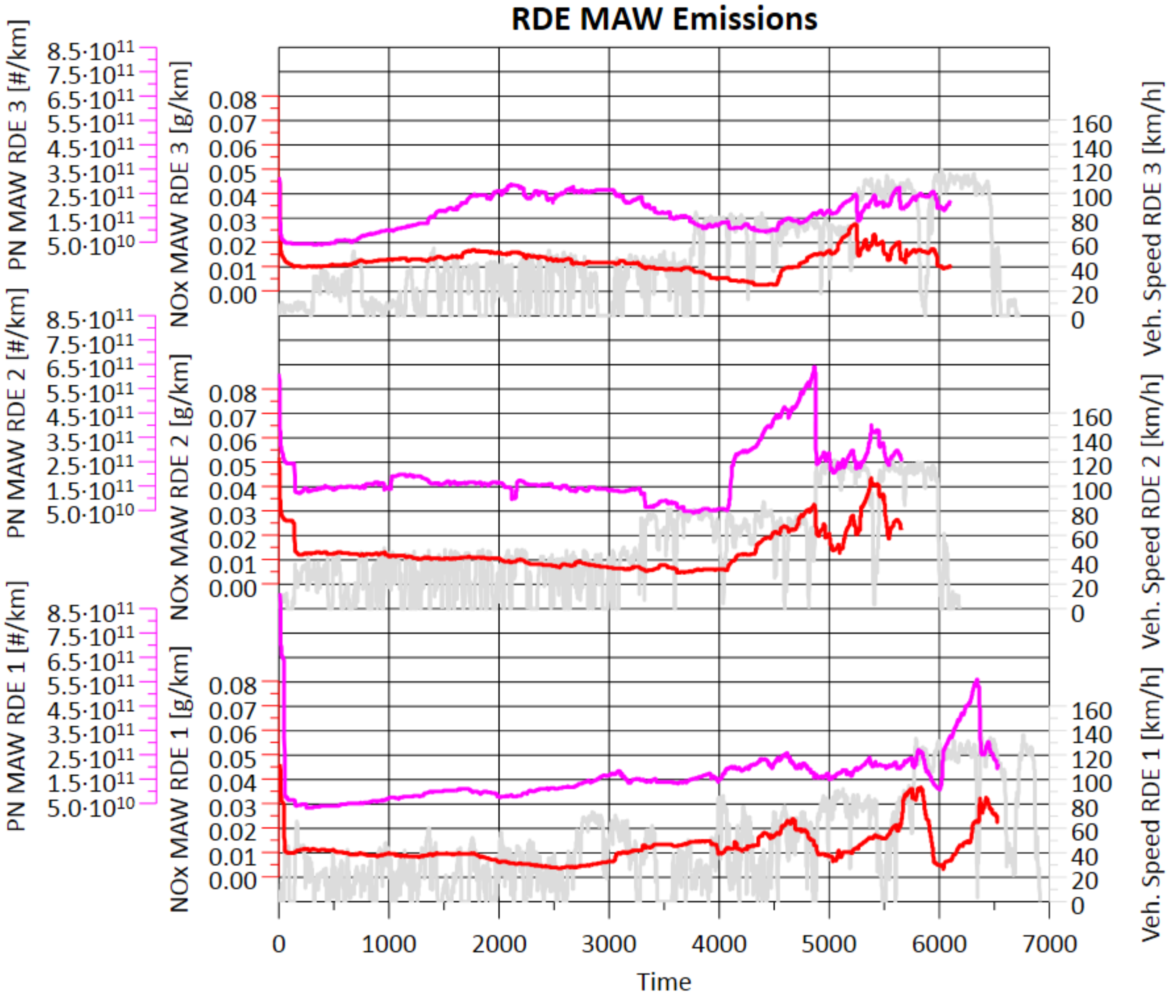


Fig. 36 – RDE MAW emissions

The worst MAWs with the worst cumulative emissions values are clearly the first ones that include the cold start peak. Once the windows move out of the "cold start zone", relatively non-aggressive urban phase with low speeds get averaged and the emissions are low. There is not a significant difference in MAW emissions in transition to rural part (except the RDE 3 test in which the vehicle speeds at the beginning were really low) and the values are comparable during the most of the length of the tests. As soon as the first highway acceleration gets involved into the windows, the MAW emissions start to rise and fluctuate (depends on the dynamics/aggressivity).

10.1 Highway Emissions Peaks

It would be an extensive and complex task to analyze highway emissions peaks and to find their main causes. The potential and most common reasons for emissions peaks occurrence at higher speeds will be summarized below. Detailed analysis would be beyond the scope of this thesis.

At high speeds, engine loads, rpm and thus high exhaust volume flow, catalyst might not be able to "process" or "catch" all the exhaust gases. If this assumption was correct, CO peak would occur simultaneously with the NOx peak. CO emissions are normally fully processed by the catalyst and thus kept on relatively very low levels.

Another common cause of higher emission during high speed accelerations could be imperfectly optimized lambda regulation. In fact, it is always a great challenge for OEMs and calibration engineers to make lambda regulation work properly at all operation modes. As the sensor is usually located in the exhaust, it is very hard to regulate the air/fuel ration flowing inside the cylinders when the power demand changes dramatically in very short time (acceleration). Because of this regulation behavior, a leaner mixture at beginning of the acceleration can occur which usually results in the NOx peak. This could be proved or disproved by measuring the amount of oxygen in the exhaust.

There is usually a trade-off between PN and NOx emissions, meaning that if NOx peaks were caused by lean mixture, PN peaks occur usually due to combustion of rich mixture. Analogically, PN peaks could be caused by imperfect lambda regulation.

One important argument is that the frequency and magnitude of accelerations are limited – there is always a desired cruising speed and a speed limit. However, as illustrated in Fig. 35 and Fig. 36, highway driving could contribute to the RDE test result very significantly.

The highway emission peaks are mostly of dynamic character – acceleration, shifting etc. However, there could be periods of higher emissions caused by the current calibration mode of the engine. This problem will be addressed in the following part.

10.2 Engine Modes and Periods of Higher Emissions

In Fig. 37, different engine modes (blue line) during a cold start are shown. Engine mode can be understood as a calibration designed especially for unique operation conditions in order to optimize engine behavior, emissions, fuel consumption etc. There is a big number of different modes and each has its specific purpose. The most basic and important categories are normal (in-action) modes when the engine is under load and power output is demanded by driver; idling modes when there is no demand for power output; and so-called cut-off modes when the engine is engaged, but the power demand is negative – “engine-braking”.

Note that the Y-axis always represents the proportion of the certain range of values among all the points of all the tests (in this case). For example, in Fig. 37, the proportions of TWC heating mode are in hundredths on percent compared to in-action warm up mode which proportions are in percent.

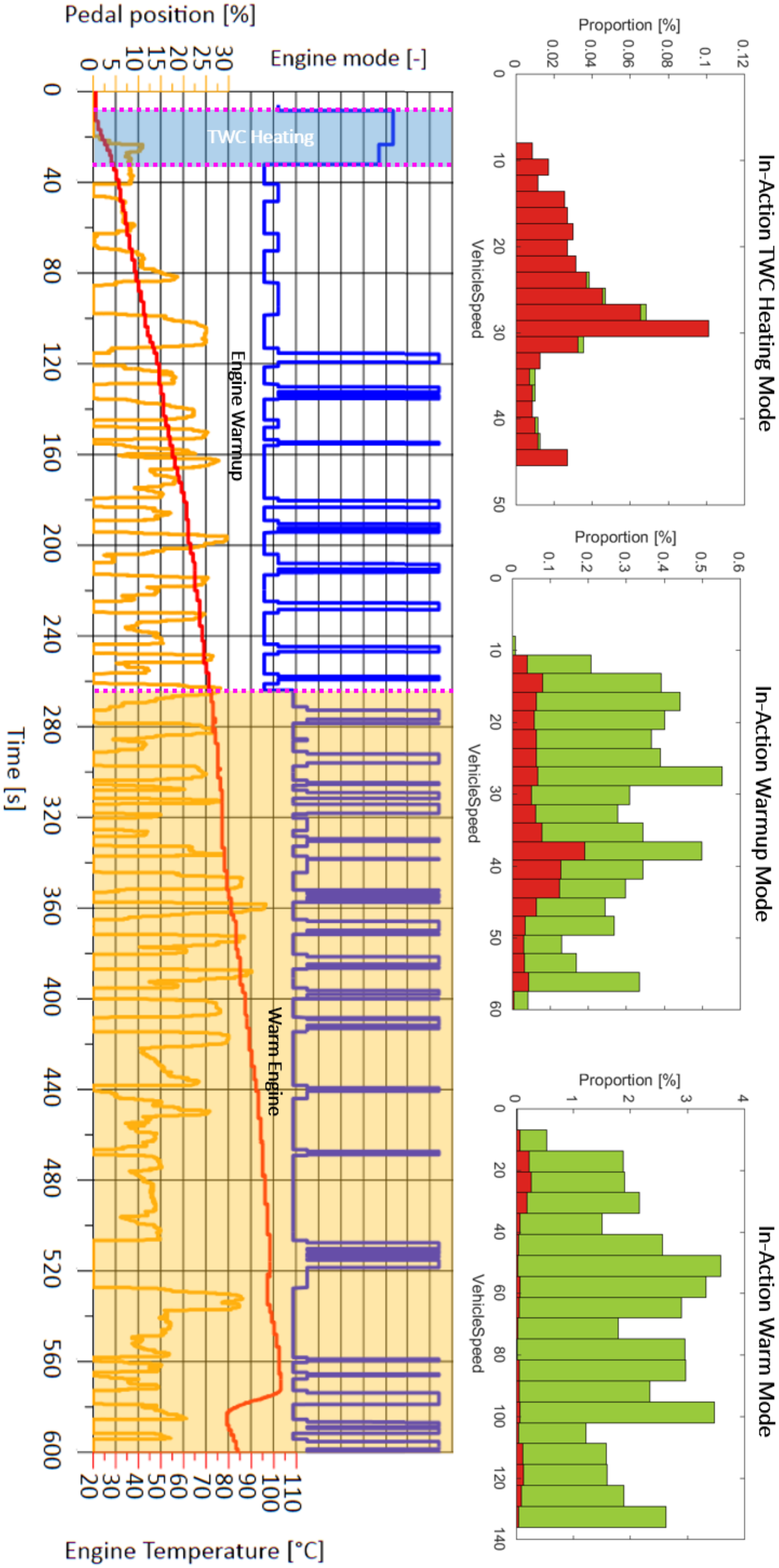


Fig. 37 – Engine modes comparison (vehicle speed [km/h])

In order to further examine risky engine modes, Ricardo RDE Data Mining Tool completed by scripts for extracting certain engine modes was used. In-action TWC heating mode, in-action warm-up mode and in-action warm mode are shown in Fig. 37.

In-action warm calibration mode is the most common among all the engine modes and is optimized very well – only 4 % of all the points operated in this mode were above NOx emissions limit line. In-action warmup mode is active until the engine temperature reaches 70 °C – 21 % of all the points in this mode were risky. By looking at the Fig. 37, it is clear that the purpose of TWC heating mode is to warm up the catalyst as quickly as possible and it is justified by the emissions produced during this mode – over 97 % of all the points in this mode were risky.

It is important to be aware of y-axis of all the emission charts in Fig. 37. The proportions of TWC heating are much lower than those of the warm calibration mode.

10.2.1 Differences between Engine Modes

How do the modes differ from each other and what makes the TWC heating mode so bad in terms of emissions performance?

To demonstrate the major differences between the engine modes, RDE Data Mining tool charts for excluded engine modes without any emissions risky areas highlighted are shown in Fig. 38. They illustrate just the proportions of each mode spent in certain operating condition. The differences can be best observed on idling modes, where the conditions are stabilized in most cases and there is less of an impact of transitions between modes. In Fig. 38, points spent in idling TWC heating mode and idling warmup mode are shown. For comparison, all the points in all modes are shown in Fig. 40.

Among the most relevant channels in order to represent the differences are engine speed, ignition angle and lambda.

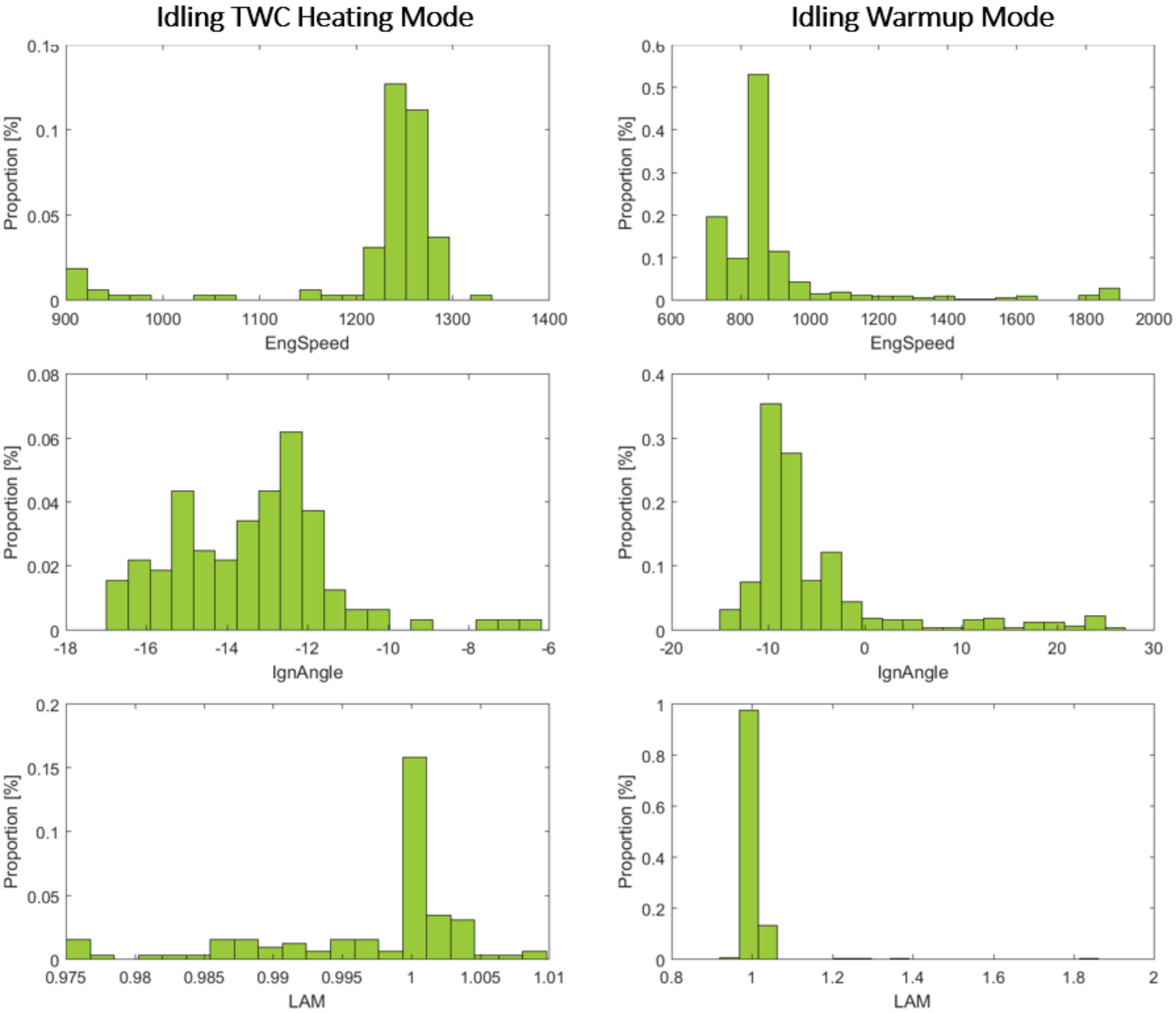


Fig. 38 – Excluded idling modes (eng. speed [rpm]; ignition angle [°BTDC]; lambda [-])

The higher engine speed in the first minute after the engine start is a known phenomenon probably to all of us. The twice as high idling engine speed during TWC heating (around 1 300 rpm) that in warm mode (around 750 rpm) is a common practice. The temperature of TWC should be increased as soon as possible to the at least 300 °C for the proper conversion of all pollutants to take place. The higher the engine speed, the more exhaust flow and more heat for the aftertreatment. Once the catalyst is heated to certain extent, the ECU switches to warmup mode, in which is the idling engine speed still higher (around 900 rpm) than in warm mode. Warmup mode is optimized to warm the whole engine faster to the threshold of 70 °C. After reaching this value, the engine is considered to be warm. The impact of these idling engine speeds could be observed in RDE PN analysis of cold start from previous part (bigger proportions at 1 300 and 900 rpm) – see Fig. 39.

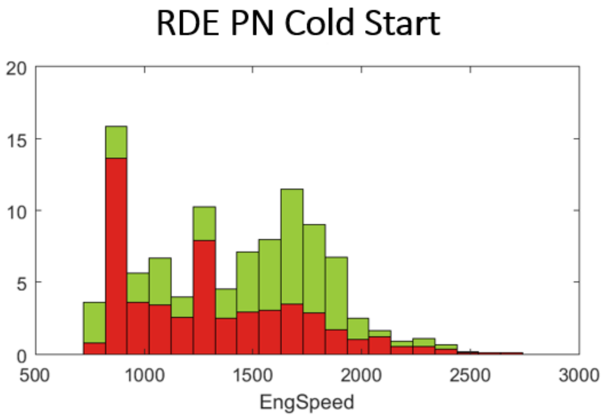


Fig. 39 – RDE PN cold start analysis (engine speed [rpm])

Very interesting difference between modes can be demonstrated on ignition angle. The theory behind ignition angle can get complex but for the purposes of this thesis, just a short introduction is given.

Ignition angle of timing refers in this case to a crankshaft angle of the release of a spark in the combustion chamber before a piston reaches the top dead center (°BTDC). The convention is thus for the angle before TDC to be positive and after TDC to be negative. In order to maximize the performance and thermal efficiency of an engine, the mixture in usually ignited around crankshaft angle of 10 to 15 °BTDC. This way, the peak of combustion occurs 6-9° after the TDC, pushes the piston down and uses the energy most effectively.

However, the main goal of TWC heating and warmup mode is neither thermal efficiency nor low fuel consumption. The later the mixture gets ignited, the lower performance and thermal efficiency the engine has. In other words, the energy and heat of the combustion is "wasted" and sent to the exhaust pipe. Fig. 38. shows that the ignition timing in TWC heating mode is retarded as far as 17° of crankshaft angle after TDC. This way, the whole aftertreatment and the engine are warmed up much faster and the trade-off between the time spent in these modes and the overall performance of the cold start period must be carefully optimized by calibration engineers.

Retarding of the ignition timing is used during shifting via automatic transmission as well. The engine torque drops instantaneously with the ignition angle shift – torque reduction and no need to adjust the engine speed (reduction of engine's thermal efficiency); analogy to clutch in manual. This might be the reason for the overall ignition angle distribution in Fig. 40.

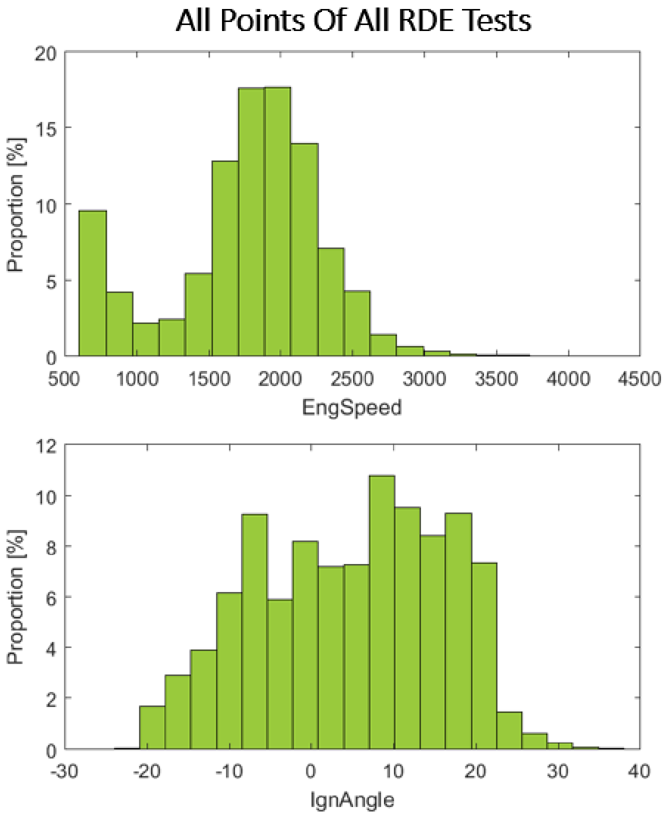


Fig. 40 – All the points of all the RDE tests distribution over engine speed [rpm] and ignition angle [°BTDC]

The last channel in Fig. 38 is lambda. It could be difficult to make conclusions due to dew point problematics[3] – the fact, that lambda is not able to measure from the very beginning at the test or drive. However, it can be stated, that rich mixture is injected especially during TWC heating since the goal is to get as much heat as possible to the exhaust and make the engine start robust enough. Since the cylinder walls are cold, fuel condensates on them and that may be the most relevant cause of PN peak at the beginning of the drive even with no acceleration.

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[3] Lambda sensor is not measuring until all the condensed water in exhaust vaporizes. The vaporization is usually finished a few tens of seconds after start, when exhaust pipe wall temperature reaches at least 55 °C. Measurement before this threshold could damage the sensor.

11 TWC Heating

Based on the RDE data analysis and information from previous parts of this thesis, I have decided to demonstrate the potential of improving passenger car emissions of the very start of the engine and TWC heating.

In order to get a better idea of how does the TWC heating mode behave and how it differs depending on start temperature, two WLTC cold starts were compared.

In Fig. 41, WLTC cold start at -7 °C (blue line) is compared with WLTC started at 23 °C (orange line). Starting from the bottom chart, vehicle speeds are the same (an advantage of the good WLTC repeatability). However, the engine modes are different since the most important input for ECU cold start algorithm is the start temperature. At -7 °C the engine speed is slightly higher, but the most noticeable difference is in the amount of injected fuel and the angle of ignition BTDC. The colder start requires the ECU to inject more fuel and retard the ignition timing in order to produce as much heat as possible.

The engine temperature as well as the TWC temperature rise steeper for the -7 °C cold start which is justified by higher fuel consumption and worsened thermal efficiency of the engine. There is a significant PN emissions peak during the first acceleration and its magnitude is directly linked to the engine temperature which is at this point still about 30 °C lower for the -7 °C start compared to the 23 °C test.

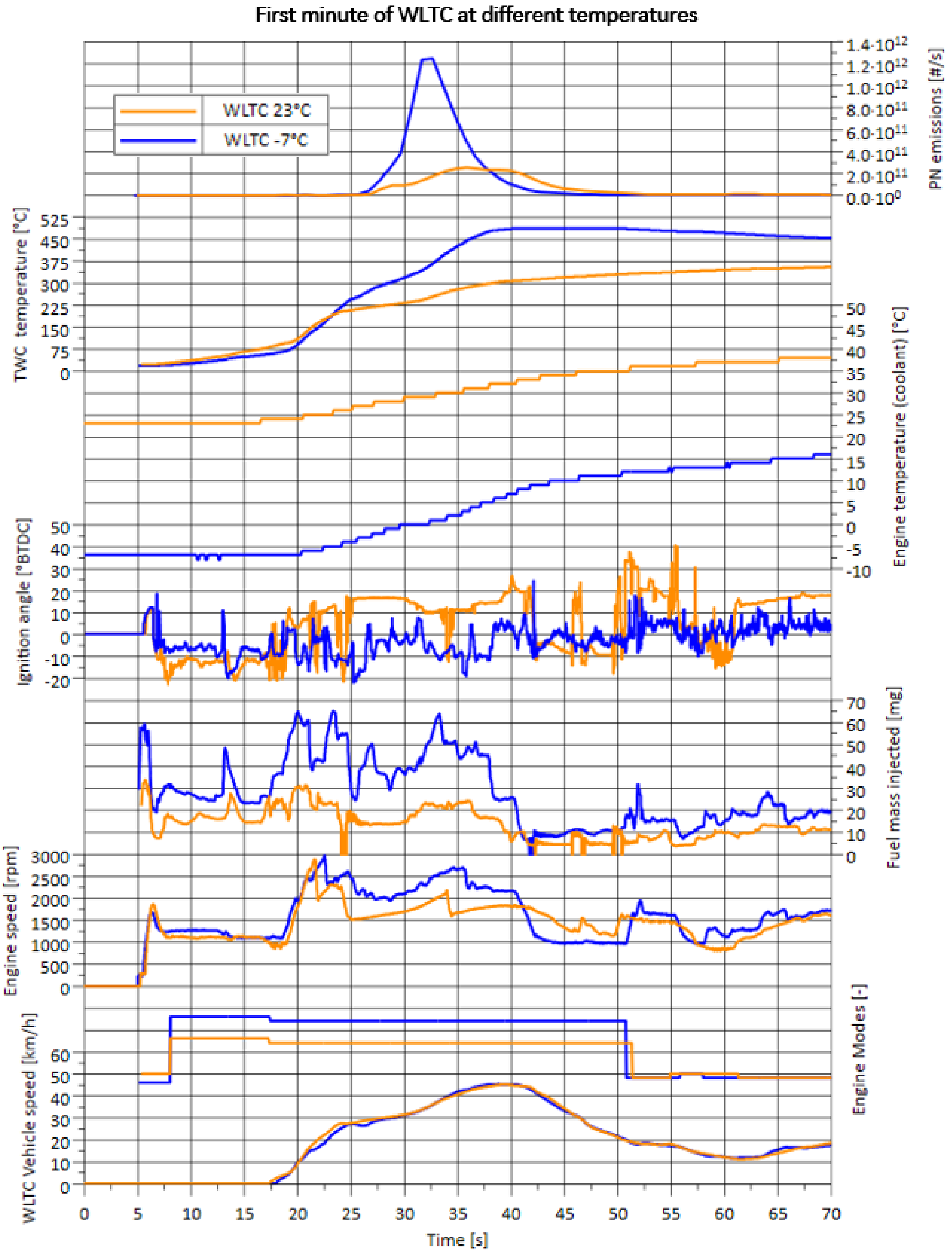

Fig. 41 – 23 °C WLTC and -7 °C WLTC comparison

It seems that the cold start emissions are unavoidable and that there is always a trade-off between emissions and engine efficiency/fuel consumption. However, Gao at al. [25] investigated possible cold start and TWC heating improvement options. The methods based on engine parameters (retarded ignition timing or air/fuel ratio adjustment) are described as low performance ones, mainly due to the significant fuel penalty and in terms of the current focus on CO_2 emissions reduction.

Among the most effective catalyst heating methods independent of engine parameters are listed for example aftertreatment system layout (reduction of the pipe length between the exhaust outlet and the catalyst inlet), heat storage materials[4] and as the most relevant – electrically heated catalyst (EHC). [25]

Heat storage materials are more practical for vehicles running regularly (engine stops shorter than 15 h) for long time at low speed, for example urban buses and airport shuttle buses.

11.1 Electrically Heated Catalyst

Based on [24] data which indicate the short length of an average trip and the fact that most of the trips include cold start, electrically heated catalyst (EHC) – see Fig. 42 – has a great potential in lowering the cold start emissions. A heater can directly heat the catalyst rather than the exhaust, and less energy is wasted with respect to the engine parameter-based methods.

Fig. 42 – Electrically heated catalyst EMICAT – Continental [26]

The transient response of EHCs is better than for thermal energy storage, because of their heat injection flexibility and independence from the IC engine operating conditions. EHCs are especially convenient in HEVs (hybrid electric vehicles), in which they consume the energy stored in the battery during regenerative braking and cruising. [25]

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[4] IC engines waste almost 50 % of the heat through the exhaust, coolant and lubricating oil. Heat storage materials can be used to partially recuperate thermal energy after the engine is warm, for pre-heating the IC engine, i.e., for warming it up before it is switched on. [25]

Fig. 43 shows an example of exhaust temperature profile with and without EHC during a part of the NEDC. The EHC shortened the TWC light-off time from 60 s to 15 s. [25]

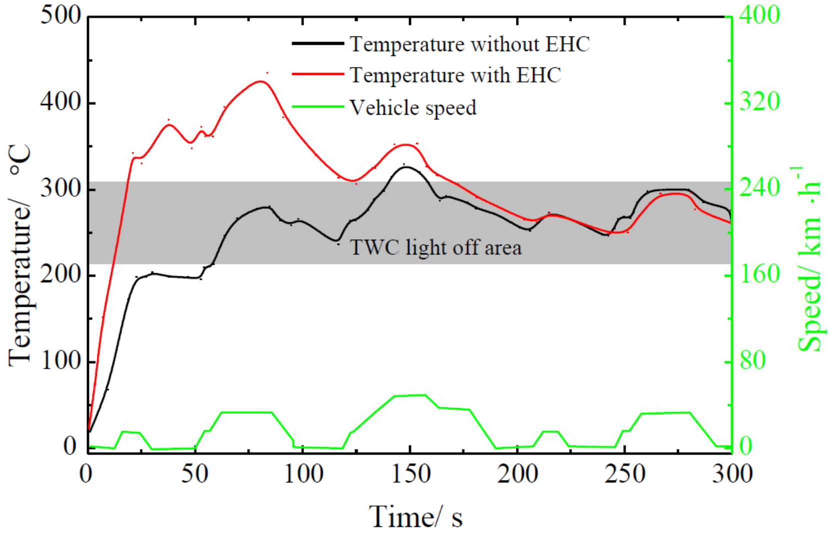

Fig. 43 – Exhaust temperature and vehicle speed profiles with and without EHC during a part of the NEDC [25]

The system response would have been further improved by a more advanced EHC control strategy. With the most obvious advantage of flexibility of heat injection in terms of position and flux, EHCs are also characterized by high energy utilization efficiency and low thermal energy transfer to the atmosphere. [25]

Nevertheless, the EHC consumes electric energy, which is eventually generated from fuel consumption. As the literature does not cover such topic in detail, the overall efficiency improvement associated with the EHC, in comparison with other methods such as additional fuel injection, needs further investigation. [25]

It is also worth noting that standard passenger car systems running 12 V batteries are probably not sufficient for EHC application and at least 48 V should be considered. In reality, EHC would be combined with other methods such as secondary air injection, which brings another variety of options of optimizing the cold start.

12 Conclusion

Real driving emissions is one of the most important topics for automotive industry these days (besides from the impact of COVID-19 pandemics). This testing methodology is not going to be in effect only in Europe, but also in other parts of the world, e.g. China, which is the biggest automotive market in the world.

The RDE procedure with cold start included was an essential step in direction of less air pollution from more environmentally friendly traffic. It forced OEMs to introduce new engine parameter-based solutions as well as innovative aftertreatment technology.

However, RDE and WLTP are not perfect as there are still conditions in real-world driving which are not captured in these tests and we will certainly see these testing procedures evolve and mature in the future. Post Euro 6, a final set of regulations (Euro 7) is expected, this will include new pollutants and further reductions in those currently regulated. Most probably, it will have a wide-ranging scope aimed at improving air quality especially for urban areas. It is therefore important to know and understand the up to date legislation, emissions limits, testing procedures and the data evaluation process.

Based on RDE data analysis and after taking into consideration the results of Gennaro et al. data acquisition campaign [24] (the short length and the low average speed of the average trip), the very beginning of a drive and TWC heating were identified as having the greatest potential to improve the emissions of passenger cars.

The engine start and warmup period can be optimized by e.g. installation and further development of aftertreatment technology as for example the EHC. EHCs have excellent catalyst light-off time reduction capability and effectively decrease exhaust emissions.

This thesis offered many view angles onto and an insight into data analysis and demonstrated the importance of which it can be for the future calibration procedures to be more efficient.

The bachelor's thesis was written in close cooperation with Ricardo Prague s.r.o.

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Appendix 1 – RDE Data Mining Tool Analysis Charts

- Fig. 1.1 – RDE NOx Cold Start (vehicle speed [km/h], engine speed [rpm], relative air load [-], engine temperature [°C])
- Fig. 1.2 – RDE NOx Aggressive Driving (vehicle speed [km/h], engine speed [rpm], relative air load [-], engine temperature [°C])
- Fig. 1.3 – RDE PN Cold Start (vehicle speed [km/h], engine speed [rpm], relative air load [-], engine temperature [°C])
- Fig. 1.4 – RDE PN Aggressive Driving (vehicle speed [km/h], engine speed [rpm], relative air load [-], engine temperature [°C])

List of Used Software

ETAS MDA V7.2 (Measure Data Analyzer)

MATLAB 2019b

Ricardo RDE Data Mining Tool

UniPlot

Microsoft Office

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Appendix 1

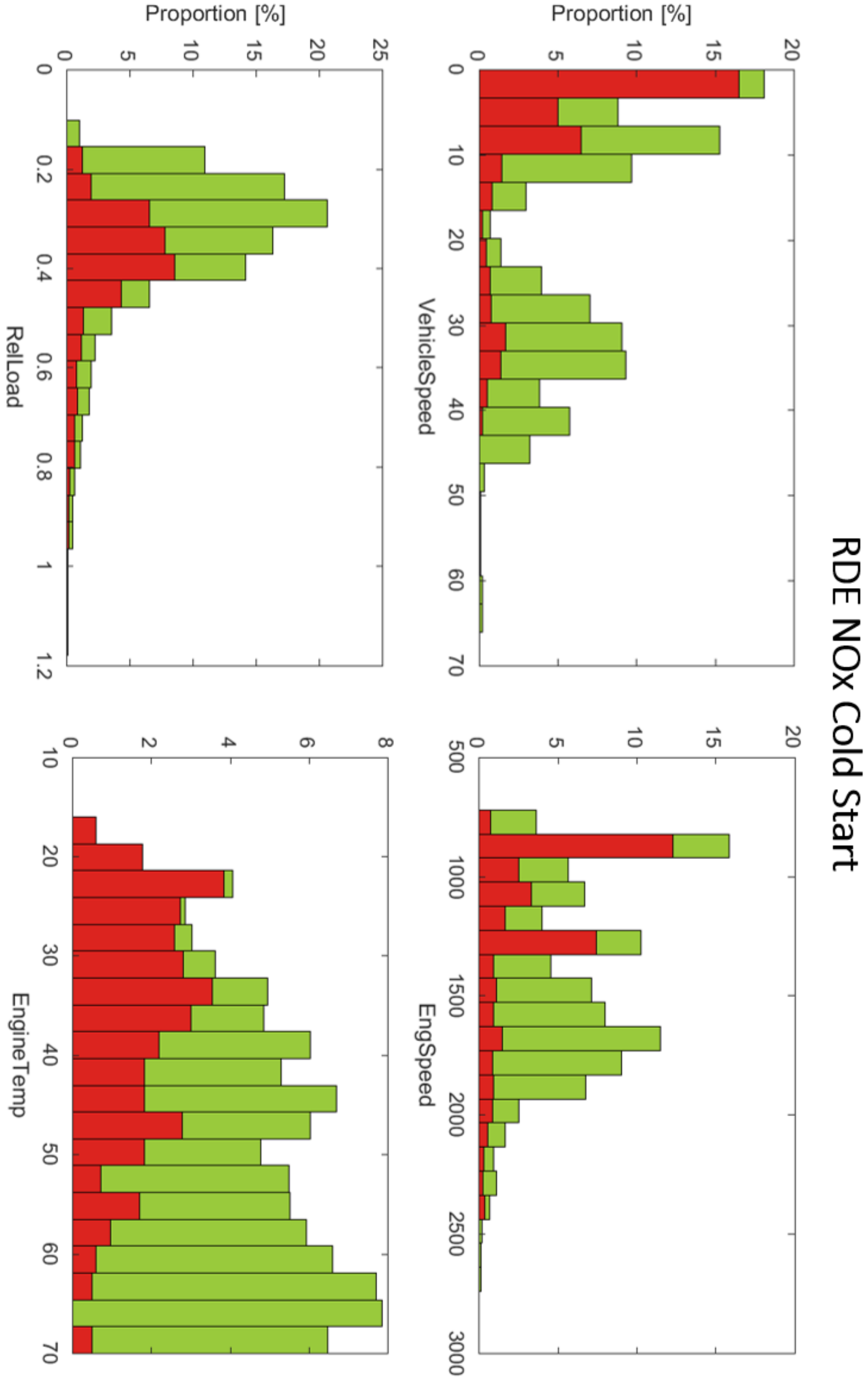

Fig. 1.1 – RDE NOx Cold Start (vehicle speed [km/h], engine speed [rpm], relative air load [-], engine temperature [°C])

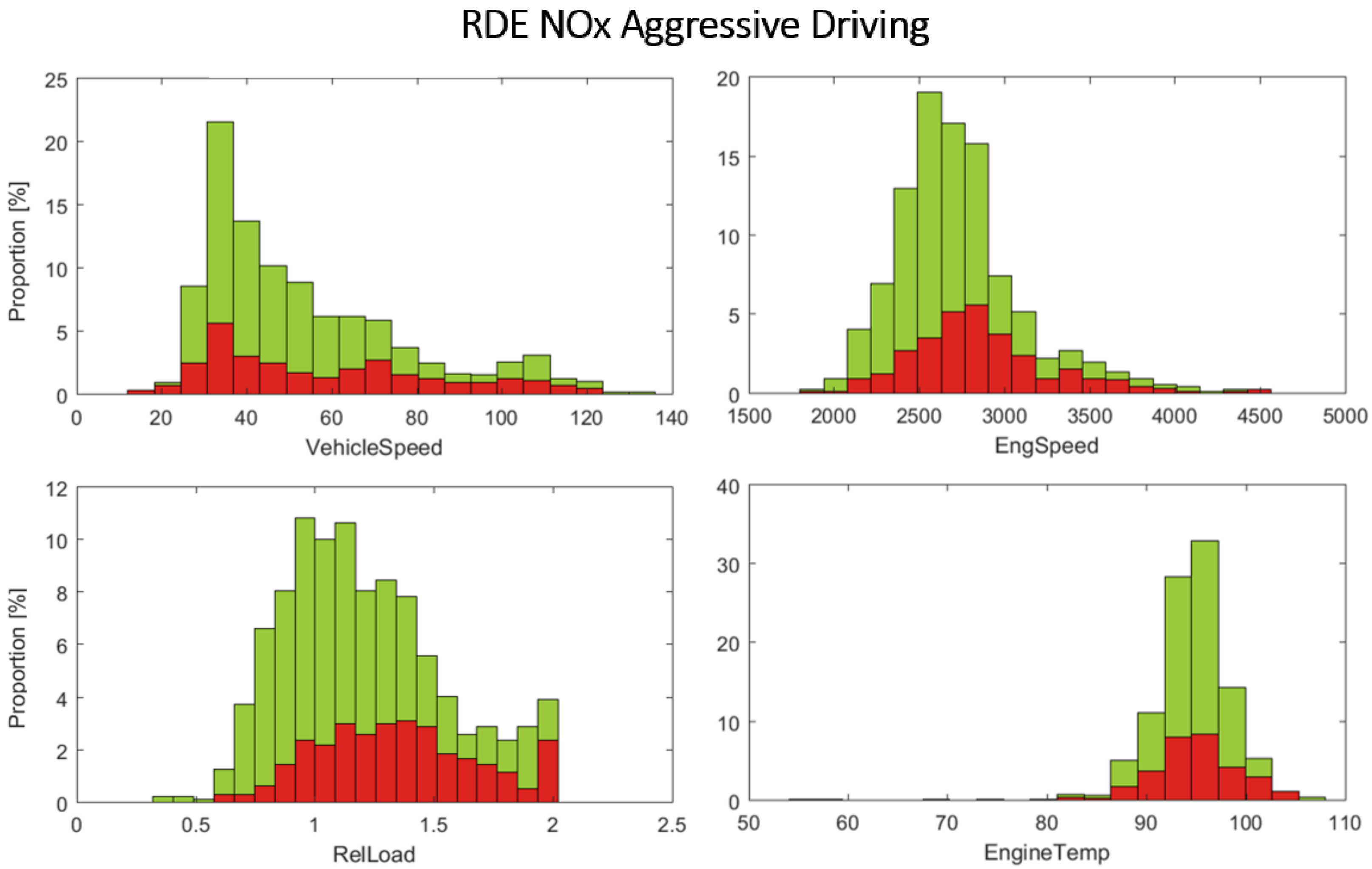

Fig. 1.2 – RDE NOx Aggressive Driving (vehicle speed [km/h], engine speed [rpm], relative air load [-], engine temperature [°C])

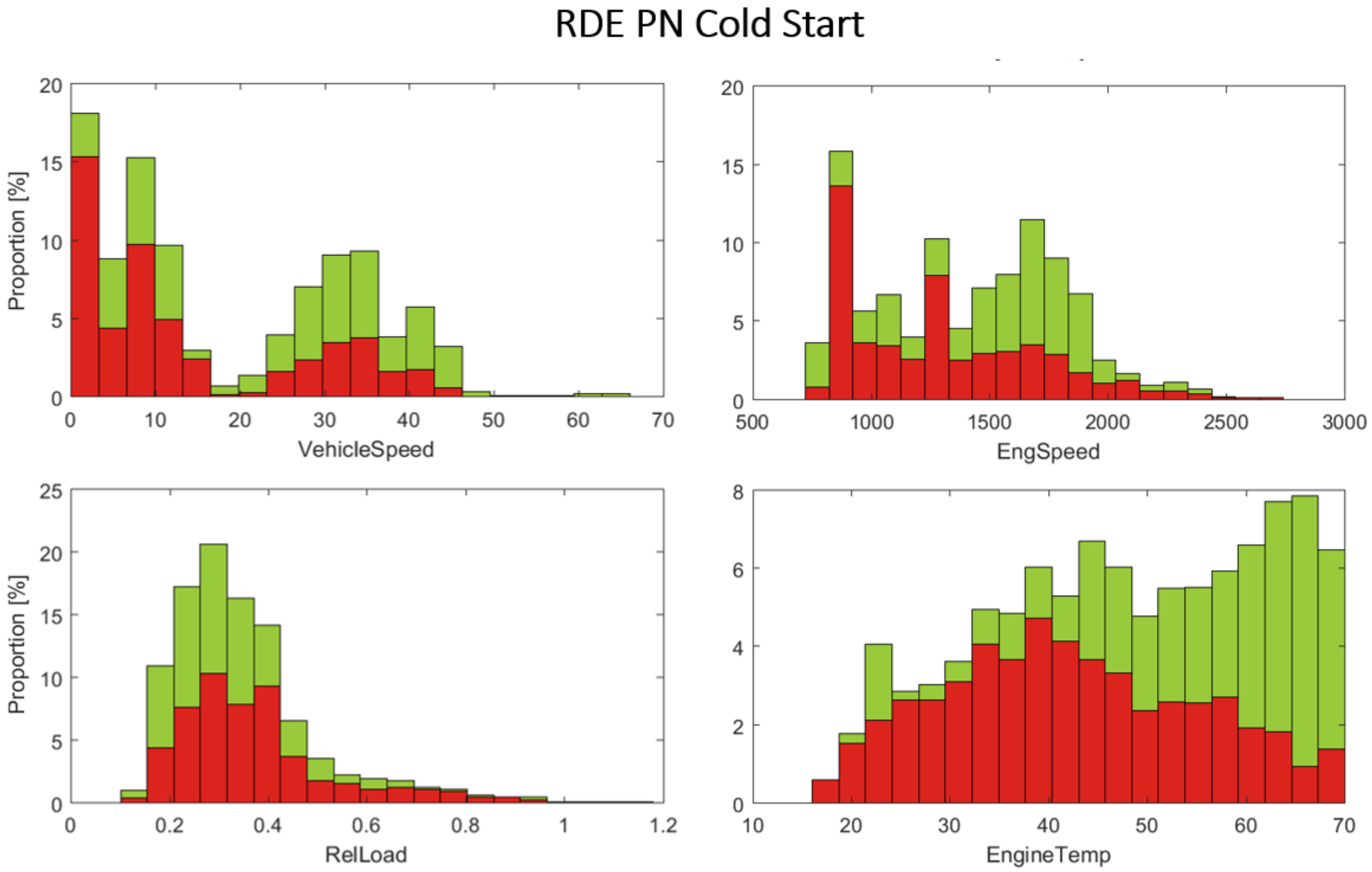

Fig. 1.3 – RDE PN Cold Start (vehicle speed [km/h], engine speed [rpm], relative air load [-], engine temperature [°C])

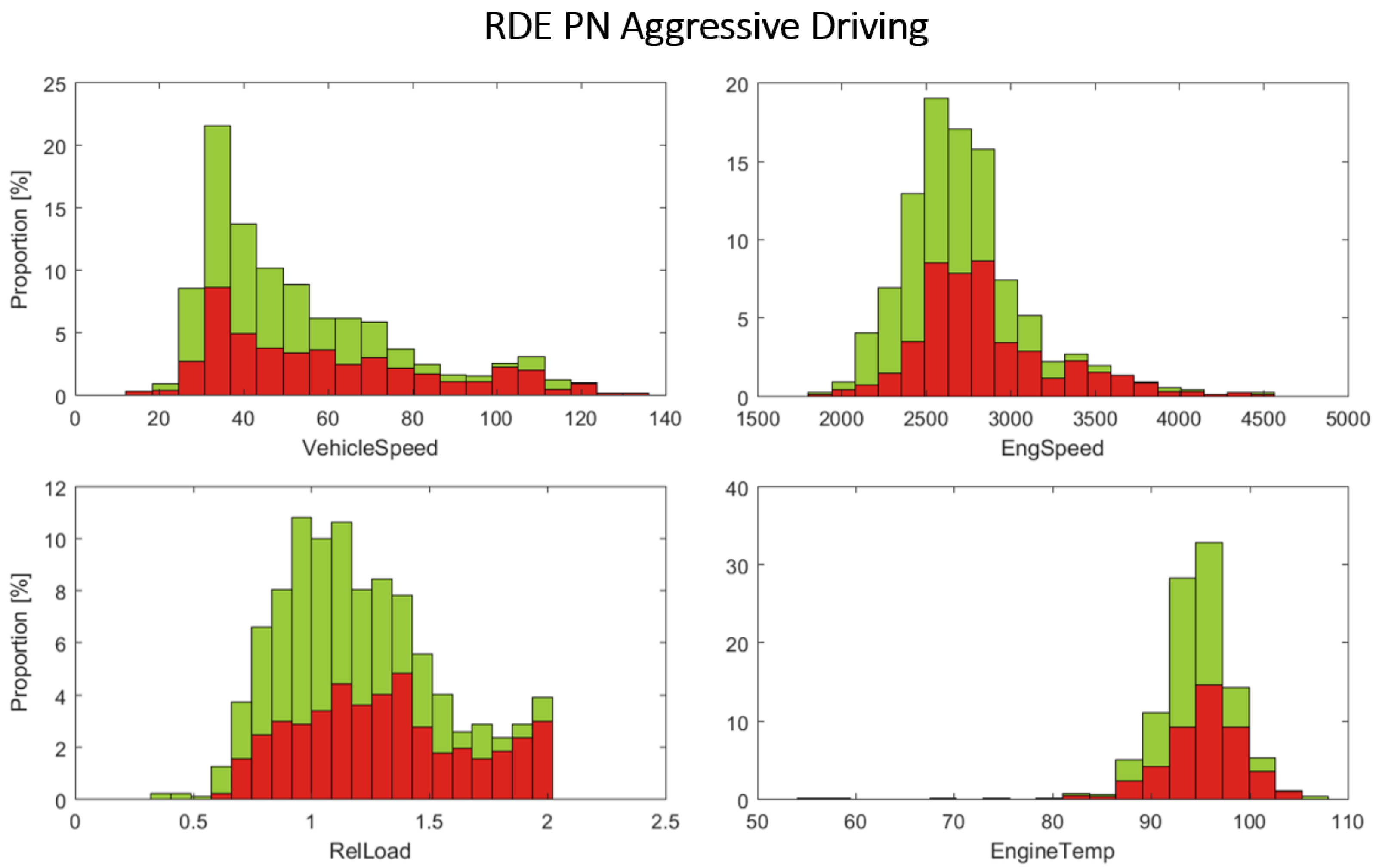

Fig. 1.4 – RDE PN Aggressive Driving (vehicle speed [km/h], engine speed [rpm], relative air load [-], engine temperature [°C])